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FLASHBACK FLAME ARRESTER DEVICES FOR FUEL CARGO TANK VAPOR VENTS

R. A. BJORKLUND

R. O. KUSHIDA

FINAL REPORT

MARCH 1981

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16. Abstract

An experimental program was conducted to evaluate the flame quenching capability of four types of flame arresting devices suitable for installation on the fuel cargo tank vents aboard marine transport vessels. The four types of flame arresters included a single 30-mesh screen, a dual 20-mesh screen, a spiral-wound, crimped metal ribbon and a packed bed of Ballast rings. The testing in a 15.2 cm (6.0 in) diameter pipe facility simulated open environment flashback flame conditions as closely as practical. Both photographic and optical flame sensors were utilized to determine flame speed and flame penetration of the test arresters. A total of eight fuels that are representative of bulk cargos were tested. These included: (1) acetaldehyde, (2) butane, (3) ethylene, (4) diethyl ether, (5) gasoline, (6) methanol, (7) propane, and (8) toluene. All four of the test arresters successfully quenched a minimum of three flashback flames from all eight fuels with one exception, high speed ethylene flames penetrated the dual 20-mesh screen arrester on three tests. All four of the test arresters successfully withstood the sustained flame from a propane/air mixture for a test duration of 30 minutes. However, none of the arresters tested withstood the sustained flame from an ethylene/air mixture for more than 7 minutes.

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PREFACE

The work described in this report was jointly sponsored by the DOT/U.S. Coast Guard, Marine Technology Division, Office of Research and Development, and NASA/Office of Space and Terrestrial Application, Technology Transfer Division, and was performed by the Control and Energy Conversion Division, Propulsion Systems Section, under the program cognizance of the Office of Energy and Technology Applications of the Jet Propulsion Laboratory.

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METRIC CONVERSION FACTORS

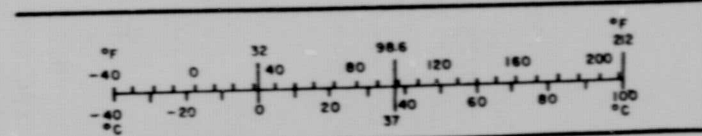
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

FIGURES

Tables

?

SECTION I

SUMMARY

An experimental program was conducted to determine the flame quenching capability of four types of flame arresters suitable for installation on fuel cargo tank vents. The four types of flame arresters included a single 30-mesh screen arrester, a dual 20-mesh screen arrester, a spiral-wound, crimped ribbon arrester, and a packed bed of rings arrester. The tests simulated the exhaust of flammable fuel/air mixtures from a cargo tank vent into an open deck environment. Ignition of the exhaust from an external source caused a flame to flash back over a finite run-up distance to the vent stack, which was protected by a flame arrester. In some tests, the flame was sustained on the arrester for durations up to 30 minutes. The flashback flame tests used eight different fuel/air mixtures to produce flames with speeds representative of those from fuels that could be carried as bulk cargo aboard typical transport vessels. The fuels used in testing were (1) acetaldehyde, (2) butane, (3) diethyl ether, (4) ethylene, (5) gasoline, (6) methanol, (7) propane, and (8) toluene. Of these fuels, propane and ethylene were used during the facility check-out, the initial screening tests, and the sustained burning tests. The standard test condition was a fuel/air mixture at an equivalence ratio from 1.0 to 1.2 (which produced the theoretical maximum flame speed for the fuel used) and a flow velocity that was low enough, 1.52 m/s (5 ft/s), to assure flame propagation back into the inlet piping in the event of an arrester failure.

The experimental program was performed at the Jet Propulsion Laboratory's Edwards Test Station (JPL-ETS) where the existing B-Stand facility provided suitable safety protection and support activities. A photograph of this test facility is shown in Figure 1-1. The facility was modified by adding a gaseous fuel system, a large flame test chamber, and a vertically directed, sustained burning test stand. The fuel/air supply and induction system provided a continuous flow of flammable mixture into a 23.8-m (78-ft.) length of 15.2-cm- (6-in.-) diameter piping. The flame arrester test assemblies were mounted at the end of the facility piping to simulate the vent stack configuration aboard a tank vessel. Optical flame sensors, pressure sensors, and thermocouples were installed in the facility piping to witness and record any flame penetration. A 2.44-m- (8-ft.-) diameter by 4.27-m- (14-ft.-) long cylindrical chamber provided a protecting enclosure surrounding the test arrester and the flow area for a considerable distance downstream. The open ends of the test chamber were covered with a thin opaque plastic film to prevent wind dilution and dispersion of the flammable fuel/air mixture plume, but offered minimal restriction to the expanding gases after combustion. An exhaust collector and burn-off stack located at the downstream end of the test chamber maintained atmospheric pressure within the chamber before ignition, and provided a means of reducing atmospheric pollution from the unburned fuel/air mixtures passing through the chamber. Optical flame sensors, pressure sensors, and a high-speed motion picture camera were used in the flame test chamber to witness and record ignition and flame propagation. It was possible to ignite the fuel/air mixture from two different locations: (1) at the upstream end of the chamber, close to the face of the test arrester, and (2) at the downstream end of the chamber where the distance was sufficient to insure that the flame propagating upstream had achieved steady-state speed upon reaching the test arrester. The

Figure 1-1. B-Stand Facility, Edwards Test Station

hydrogen/air spark igniters located at these two positions were controllable in both duration and flow rate, making it possible to minimize the momentum imparted to the resulting flame.

Facility checkout tests were made with a subscale flame chamber and a full-scale flame chamber using both gasoline/air mixtures and propane/air mixtures. Test operating procedures and instrumentation techniques were developed that resulted in repeatable flame propagating conditions and reliable flame-speed measurements. The frangible plastic diaphragms covering the ends of the flame test chamber were effective in containing the fuel/air mixture plume prior to ignition and limited the nominal peak pressure rise in the chamber to around 1000 N/m^2 (0.145 psid), when they were ruptured by the combustion wave. There were no detonations in either the test chamber or the facility piping from the flashback flames during facility checkout tests.

An initial series of screening tests were made in the full-scale flame test chamber using propane/air mixtures and ethylene/air mixtures (as representative of the two extremes of probable flame speeds for typical bulk cargo fuels) to determine which igniter location (upstream or downstream) produced the most severe test conditions. The severity being identified as the highest flame speed propagating upstream towards the test flame arrester. Both the single 30-mesh screen arrester and the dual 20-mesh screen arrester were evaluated for flame quenching capability on these tests. The resulting flame speeds ranged from 2.99 to 6.60 m/s (9.81 to 21.65 ft/s) with the upstream igniter location producing the higher flame speed for both fuel/air mixtures. A tabular summary of average values of flame speeds and peak pressure rises for all fuels tested is given in Table 1-1. The single 30-mesh screen arrester quenched all flashback flames for both fuel/air mixtures. The dual 20-mesh screen arrester quenched all propane/air mixture flames and the ethylene/air mixture flames initiated by the downstream igniter location. The ethylene/air mixture flames initiated by the upstream igniter location penetrated the dual 20-mesh screen arrester in three successive test firings. A tabular summary of the flashback flame quenching test results for all fuel/air mixtures and test arrester assemblies is given in Table 1-2.

The upstream igniter location was used on all the subsequent flashback flame quenching tests. The single 30-mesh screen arrester and the dual 20-mesh screen arrester were tested with the six remaining fuel/air mixtures. Both arresters were successful in quenching the flames on all test firings as shown in Table 1-2. The resulting flame speeds, or test condition severities, for the six additional fuel/air mixtures were less than those measured for the ethylene-fuel/air mixture, as shown in Table 1-1.

The original test configuration for the packed bed of aluminum Ballast rings arrester was unsuccessful in quenching the flashback flames from gasoline/air mixtures in three successive test firings. A single 30-mesh screen was added on the downstream end of the arrester, between the retainer grid and the bed of rings. This modified configuration was successful in quenching flashback flames from the propane/air mixture, gasoline/air mixture, and three out of four test firings with ethylene/air mixture. The spiral-wound, crimped stainless-steel ribbon arrester was successful in quenching all flashback flames from propane, ethylene, and gasoline-fuel/air mixture test firings. The test results are summarized in Table 1-2.

The sustained burning tests were conducted outside of the flame test chamber by rearranging the facility piping. Using a combination of pipe elbows, the last section of inlet pipe was redirected 90 deg to one side and the flame arrester test assemblies were mounted on the end of the pipe in the vertically up position. Two different sizes of flame screen arrester assemblies were tested, (1) the original 15.2-cm- (6-in.-) diameter adapter housing and (2) a new 25.4-cm- (10-in.-) diameter adapter housing. This change in arrester flow area was made to evaluate the effects of the approach velocity and flow-through velocity of the fuel/air mixture on the thermal environment at the screens. The single 30-mesh screen arrester and the dual 20-mesh screen arrester in both pipe sizes, the packed bed of Ballast rings arrester, and the spiral-wound, crimped ribbon arrester were all successful in maintaining sustained burning with the propane/air mixture for the full 30 minutes (1800 seconds) of test duration.

Table 1-1. Tabular Summary of Flashback Flame Speed and Test Chamber Peak Pressure Rise

Igniter Location And Type of Fuel	Average Flame Speed at Tester Arrester: Flame Sensor Data, m/s (ft/s)		Average Flame Speed at Tester Arrester: Photographic Data, m/s (ft/s)		Average Peak Pressure Rise in the Flame Test Chamber, N/m^2 (psid)	
Downstream						
Propane	2.99	(9.81)	3.38	(11.09)	814	(0.118)
Ethylene	4.35	(14.27)	4.02	(13.19)	931	(0.135)
Upstream						
Propane	4.75	(15.58)	3.40	(11.15)	1043	(0.151)
Ethylene	6.60	(21.65)	4.75	(15.85)	1102	(0.160)
Gasoline	4.22	(13.85)	2.42	(7.94)	1020	(0.148)
Methanol	4.35	(14.27)	3.18	(10.43)	831	(0.120)
Toluene	5.42	(17.78)	3.21	(10.73)	668	(0.097)
Diethyl ether	5.61	(18.41)	3.73	(12.24)	937	(0.136)
Butane	3.62	(11.88)	2.90	(9.51)	926	(0.134)
Acetaldehyde	5.30	(17.39)	4.64	(15.22)	1102	(0.160)

Table 1-2. Tabular Summary of Flashback Flame Quenching Test Results

Igniter Location And Arrester Configuration	Type of Fuel and Number of Flames Quenched															
	Propane		Ethylene		Gasoline		Methanol		Toluene		Diethyl Ether		Butane		Acet-aldehyde	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Downstream																
Dual 20-Mesh screens	3		3													
Single 30-Mesh screen	4		3													
Upstream																
Dual 20-Mesh screens	3			3	3		3		3		3		4		3	
Single 30-Mesh screen	3		3		3		3		4		3		3		3	
Packed bed of Ballast rings						3										
Packed bed of Ballast rings with single 30-mesh screen	3		3	1	3											
Spiral-wound, crimped ribbon	3		4		4											

Sustained burning tests were also made with the ethylene/air mixture, but because of the anticipated severity of test conditions, only the packed bed of Ballast rings arrester and the spiral-wound, crimped ribbon arrester were tested. The spiral-wound, crimped ribbon arrester failed in two tests of 423 seconds and 383 seconds duration. The packed bed arrester failed on the first tests after only 43 seconds duration, and resulted in a deflagration-to-detonation transition in the arrester bed. On the second test, the packed bed arrester failed immediately after ignition due to a damaged screen. The results of the sustained burning tests are summarized in Table 1-3.

Table 1-3. Tabular Summary of Sustained Burning Test Results

Flame Arrester Type and Size	Type of Fuel	Time Duration of Burning, s	Flamethrough
15.2-cm- (6-in.-) diam. single 30-mesh stainless-steel screen	Propane	1800	No
15.2-cm- (6-in.-) diam. dual 20-mesh stainless-steel screen	Propane	1800	No
25.4-cm- (10-in.-) diam. single 30-mesh stainless-steel screen	Propane	1800	No
2.54-cm- (10-in.-) diam. single 20-mesh stainless-steel screen	Propane	1800	No
30.5-cm- (12-in.-) diam. by 20.3-cm- (8-in.-) long spiral-wound, crimped stainless-steel ribbon	Propane	1800	No
	Ethylene	423	Yes
	Ethylene	383	Yes
25.4-cm- (10-in.-) diam. by 45.7-cm- (18-in.-) long packed bed of 2.54-cm- (1.0-in.-) size aluminum ballast ring plus a single 30-mesh stainless-steel screen	Propane	1800	No
	Ethylene	43	Yes
	Ethylene	0	Yes

SECTION II

INTRODUCTION

The U. S. Coast Guard, under the Ports and Waterways Safety Act (PL 92-340), is responsible for the safety of vessels and U. S. ports from the inherent hazard of handling petroleum products. The Coast Guard must insure that cargo tanks aboard vessels are adequately protected from ignition sources that may be present on deck. Ships and barges that carry grades D and E flammable cargo are required under Subcharter D of Title 46 to have flame screens on the vent outlets of cargo tanks, cofferdams and void spaces, and on all open ullage holes, hatches, or Butterworth plates. The screens prevent accidental flame passage from the open deck into the cargo tank. A single 30-mesh screen or dual 20-mesh screens spaced more than one-half inch apart and not more than one and one-half inch apart are approved by the U. S. Coast Guard.

The adequacy of the flame screen as a flame arrester has been questioned (Reference 2-1). Wilson and Crowley (References 2-2 and 2-3) carried out tests for the U. S. Coast Guard with screen arresters, where the screens were mounted some 1.83 m (6.0 ft) inboard from the open end of the pipe, rather than at the end as in the standard vent-stack installations. These nonstandard installations were used for tests of screen arresters at high turbulent flame speeds, ranging from 2 to 30 m/s (6.6 to 98.4 ft/s). These tests of screen arresters were more severe than those where the screens were mounted in the standard installation. Under certain conditions, screen arresters failed to quench the flame in some of these tests. It seems, however, that the higher flame speeds were accompanied by gross gas motions that caused apparent discrepant flame quenching results. Because the Wilson and Crowley test conditions were not representative of flashback-flame propagation to a standard vent-stack installation in an open environment, more tests that simulated the actual conditions existing aboard fuel cargo transport vessels were needed. One of the major points of interest is whether or not a flame will accelerate in an open deck environment and what effect this accelerated flame speed has on the quenching capability of the screen arrester.

Screen flame arresters mounted at the end of a vent stack are designed to prevent flames ignited outside the tank from propagating into the tank. It is assumed that the flammable gases in the vent stack are either quiescent or flowing out. On the other hand, most of the reported tests on screen flame arresters confine the flame in an enclosure whose only or major outlet was through the flame arrester (Reference 2-4). Combustion within an enclosure is invariably accompanied by considerable gas flow through the screen in the direction of flame propagation. The hypothesis to be tested was whether an unconfined turbulent flame flashback can be stopped from propagating into a vent stack whose end is covered with a screen flame arrester. In these tests, it was supposed that there is no gross gas flow through the screen associated with the ignition and propagation of the flame.

Screen flame arresters are designed to completely enclose the outlet openings with a fine wire mesh. The wire mesh is sufficiently open so that it offers negligible obstruction to the passage of gases and vapors, but the mesh openings are too small to allow the passage of flames. There should be no opening in the

screen flame arrester with an equivalent hydraulic diameter[1] larger than the critical diameter of flame quenching in a tube. The critical diameters for flame quenching in a tube for a large variety of different flammable gas mixtures have been established in extensive laboratory tests, as discussed in Wilson and Attalah's review of flame arresters for cargo venting systems (Reference 2-5). It has been shown for laminar flames propagating in flammable gases that the correlation for the critical Peclet number (Pe) (Reference 2-4) is:

$$\log_{10} Pe = 1.8 \pm 0.3$$

Pe is defined as $D_{CR} \times Su/\alpha$, where D_{CR} is the critical diameter for flame quenching in a tube, Su is the laminar flame velocity in the unburned mixture, and α is the thermal diffusivity in the unburned mixture. The uncertainty in the value of $\log_{10}$ Pe allows for differences in the behavior of widely different fuels and oxidizers, but it is sufficiently restrictive to yield useful design values for the maximum allowable opening sizes in flame arresters.

The concept of quenching a laminar flame in a narrow tube through heat loss to the walls of the tube is well established (Reference 2-5). For effective flame quenching, the surface must be noncatalytic (this requirement is satisfied by all commercial materials of construction) and heat dissipative (stainless steels have adequate conductivity). Screen flame arresters differ from isolated orifices of the flame quench theory in that there are arrays of orifices. Each orifice in the array acts identically to an isolated orifice as far as flame quenching is concerned. Gas flows and heat transfer associated with flame propagation and gas volume expansion seem to be the main causes of screen failure. The flame heats and weakens the wires of the screen so that fluid friction and pressure tear openings into the wire mesh (References 2-6, 2-7, and 2-8). It is evident that prolonged exposure to sustained burning will decrease the quenching capability of the screen arrester, a phenomena that requires further investigation.

Flames propagating in open environment are almost invariably turbulent, as opposed to the laminar flames considered in the quenching theory (Reference 2-9). For most practical considerations, open turbulent flames can be considered highly wrinkled laminar flames whose characteristic wrinkle dimension is in the order of the critical diameter for flame quenching. The heat release rate is proportional to the total area of the propagating wrinkled flame front, which can be many times larger than the superficial projected flow area. The criterion for the critical diameter for flame quenching by the flame arrester is the same for turbulent and laminar flames according to Reference 2-4, but the heating effects of the turbulent flame are very much greater. In addition, the nonuniform and fluctuating turbulent flame front can cause, in pockets of the flame, the release of transient high pressure and high heat that far exceed in value the pressure and heat of a laminar flame (Reference 2-11). If a transient high reactivity pocket of gas coincides with the intersection of the flame front and the screen flame arrester, there is a probability that the flame will penetrate the screen

[1]Equivalent hydraulic diameter $= \dfrac{4 \times (\text{cross-sectional area of passageway})}{\text{perimeter of passageway}}$

at that location. To prevent such flame penetration, conservative design practice would call for screen openings substantially smaller than the theoretical critical diameter for flame quenching. Those considerations are probably the reason that Rozlovskii and Zakaznov's review (Reference 2-4) presents such a wide range of critical Peclet numbers reported by different investigators in simulation of practical fire environments.

It is important to make a distinction between "burning velocity" and "flame speed" (Reference 2-9). Burning velocity is defined as the speed of the propagation of a flame front relative to the speed of the unburned gas. It is a property of the gas composition and of the physical state of the unburned gas mixture. Flame speed is defined as burning velocity plus any gross motion in the unburned gas relative to a fixed frame of reference. It is influenced by gross gas motion and by the geometry of any enclosing structure.

The propagation of a flame in a duct can create gross gas motion. This is clearly illustrated if we consider a duct, closed at one end and open to the atmosphere at the other, filled with a flammable gas. When the gas is ignited at the closed end of the duct, the flame speed is greater than it would be if the flame were started at the open end and allowed to travel toward the closed end. In the case of closed end ignition, the burned gas is expanding and pushing the unburned gas out the open end of the duct, so that the "flame speed" is the sum of the "burning velocity" and the gross motion, which is caused by the expansion of the trapped hot combustion products. In the second case, the ignition at the open end causes the unburned gas to remain stationary, hence the observed "flame speed" is nearly the "burning velocity" with differences due mainly to flame front interaction with the duct wall.

While gross gas motion does not change burning velocity by itself, there are additional factors that cause enclosed turbulent flames to accelerate in burning velocity. Acceleration of turbulent flames in ducts has been discussed in a previous JPL report (Reference 2-10) in connection with transition from deflagration to detonation. Little understood interactions between turbulent flame propagation and the turbulent boundary layer on a duct wall can lead to appreciable acceleration of the burning velocity. The flame can be accelerated to such a high speed that shock waves become associated with the highly turbulent flame front, whereupon compressive heating causes still greater acceleration until detonation is obtained. In a confined duct, particularly in those with rough walls, turbulent flames can readily accelerate to the point where self-compressive ignition occurs. The transition from deflagration to detonation in hydrocarbon-fuel/air mixtures is an extremely improbable event in an open environment, but detonations can be initiated by a shock wave from an external source, such as a bomb (Reference 2-11).

Pipes carrying vapors out of cargo tanks that contain volatile flammable liquids may contain a fuel/air mixture within the flammable range, as illustrated in Figure 2-1. A source of flame ignition outside the vent stack, as illustrated in Figure 2-2, may cause a flame to propagate into the vent stack. Flame propagation within a narrow pipe is particularly dangerous, because both confinement of the expanding hot combustion products and flame front acceleration due to interaction with the wall boundary layer can occur. In severe cases, the flame propagation can become a destructive detonation wave. The illustration in Figure 2-2 shows a flame front accelerating inside a pipe in contrast to the uniform rate of propagation in the open air.

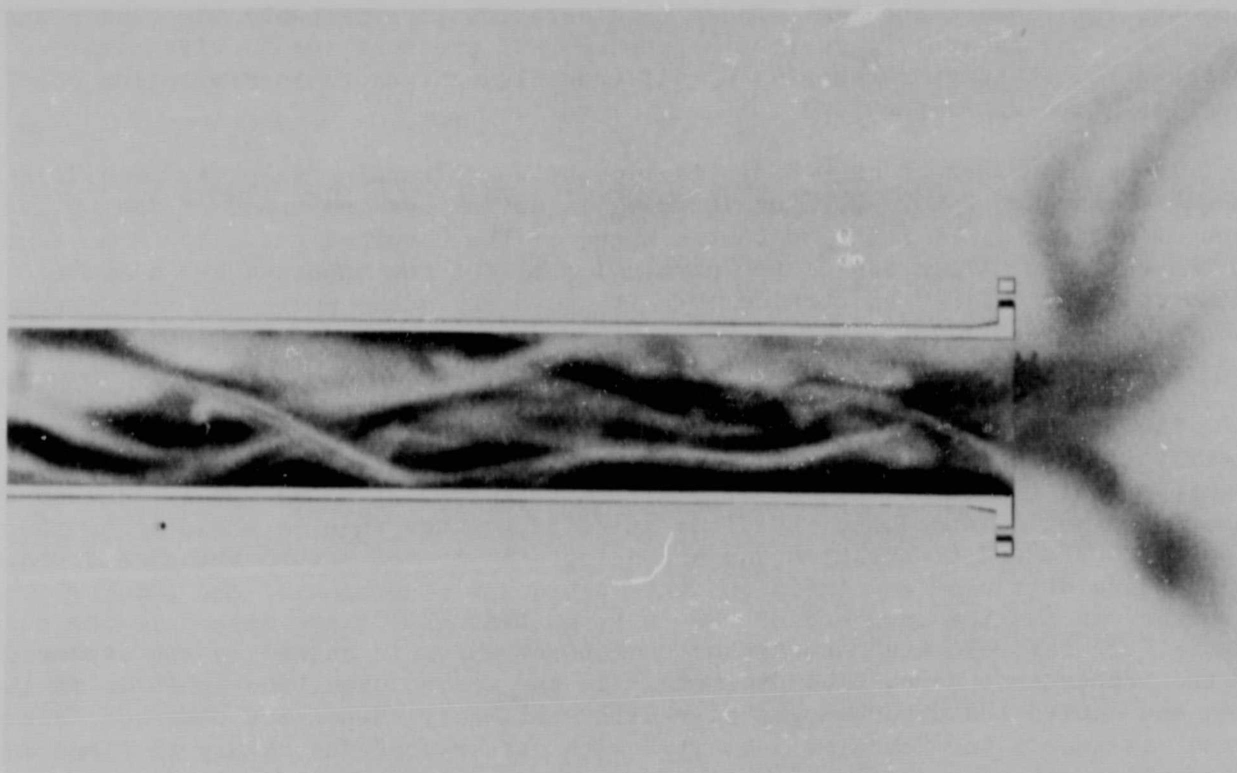


Figure 2-1. A Flammable Fuel/Air Mixture Flowing Slowly Out of a Vent Stack Into the Open Air

The installation of a simple screen flame arrester to close the open end of the vent stack to flames while still allowing free flow of vent vapors is shown in Figure 2-3. Here the flame from an outside ignition source does not propagate into the vent stack, but impinges on the surface of the screen. If the equivalent hydraulic diameter of the openings in the wire mesh of the screen flame arrester are smaller than the critical diameter for flame quenching, then the flame will be stopped by the screen. The concept and theory of the critical flame quench diameter has been reviewed by Wilson and Attalah (Reference 2-5). The flame, can, however, continue to burn on the surface of the screen if there is a flow of flammable mixture through it. The continued heating can lead to flame flashback if the wire screen's temperature becomes high enough. One element of the program was to test susceptability to flashback due to continued burning on the surface of the screen flame arrester.

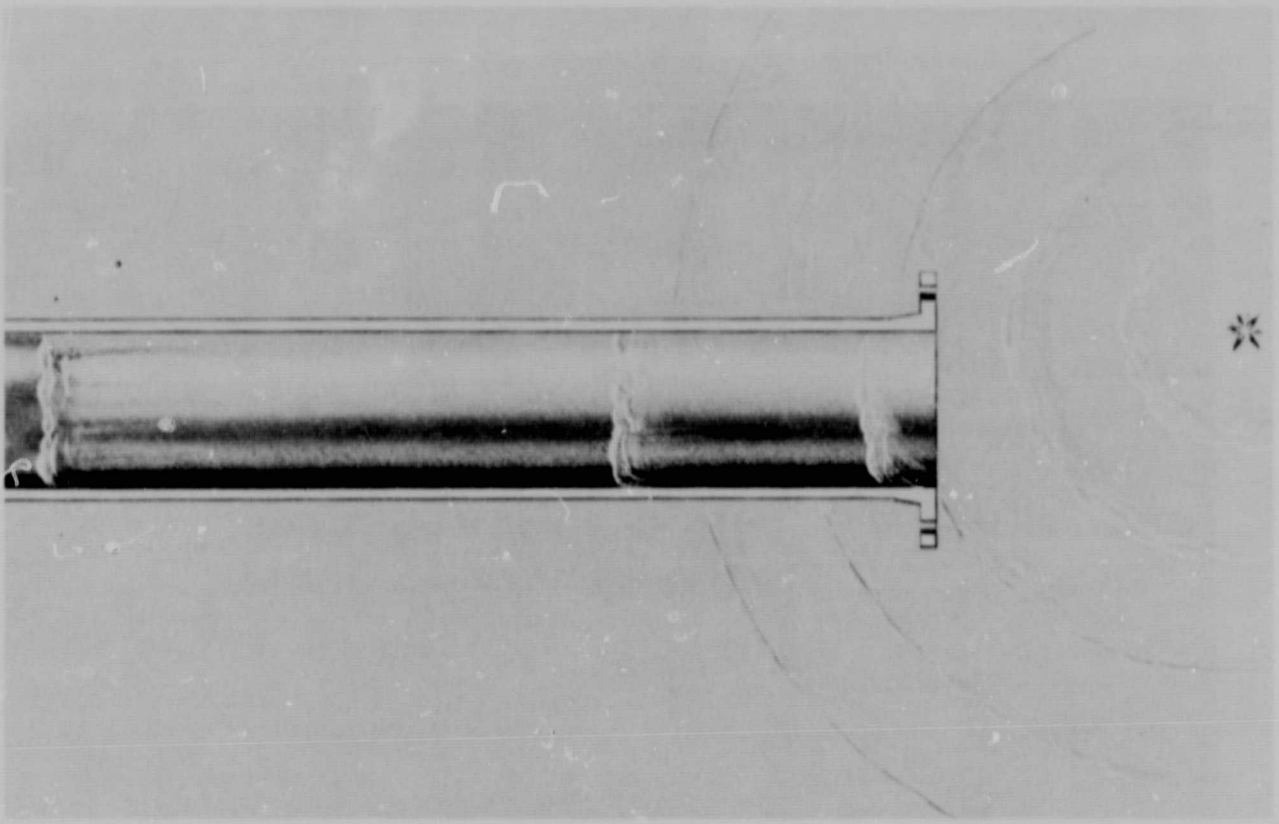


Figure 2-2. An External Ignition Source Sends a Spherically Expanding Flame Front Propagating Into the Flammable Mixture in the Vent Stack

If the screen is mounted internally in the vent stack as shown in Figure 2-4, the flame arresting effectiveness of the screen is reduced. Upon entry into the open end of the vent stack, the flame accelerates. The accelerated flame speed causes the pressure to rise ahead of the flame front, and, if severe enough, push the flame through the screen. The gas flow in the pipe can be momentarily reversed so that the flame front and the gas flow both propagate in the same direction, which is through the screen flame arrester. Once the flame has penetrated the screen, the situation is even more dangerous since the failed screen flame arrester now acts as a barrier to hot gas flow, and thus causes an even greater acceleration of flame speed and a greater likelihood of detonative combustion.

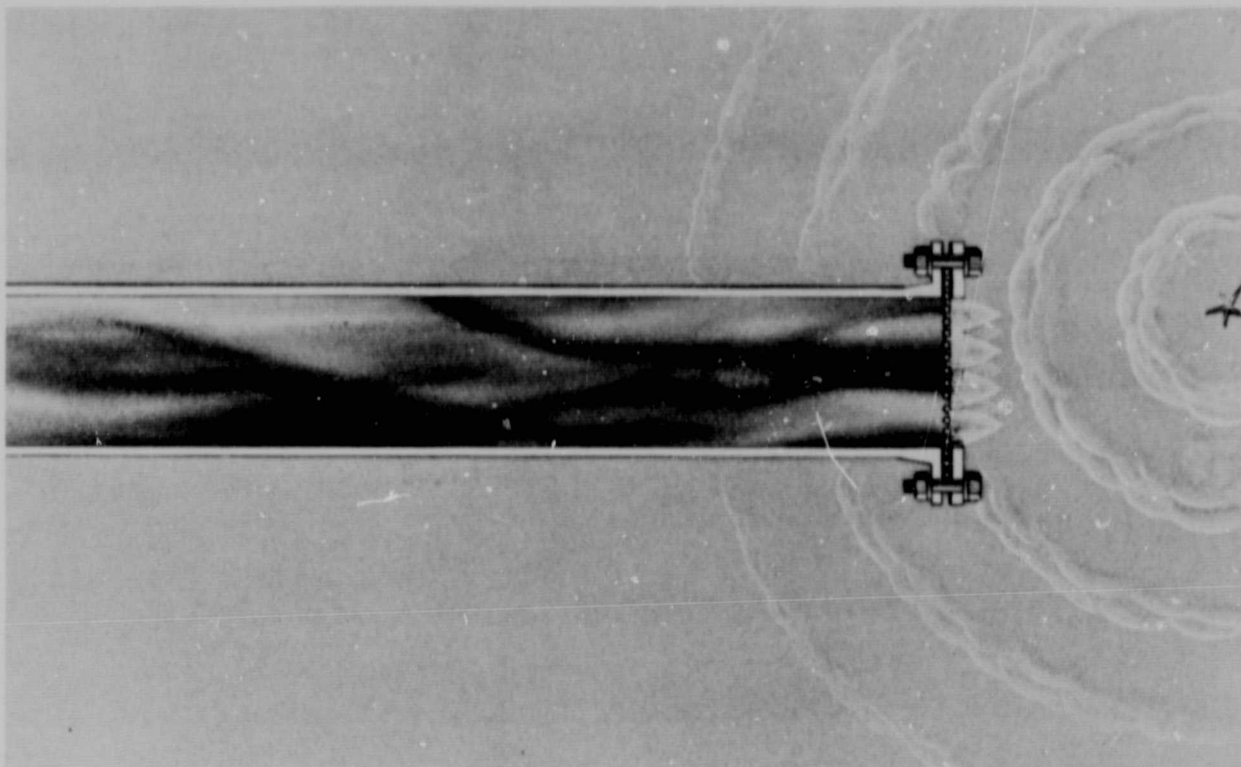


Figure 2-3. A Propagating Flame Front Impinges on a Screen Flame Arrester Mounted on the End of the Vent Stack and Does Not Enter the Piping

A screen flame arrester damaged by a hole may fail to arrest a propagating flame if the hole diameter is larger than the critical diameter for flame quenching. The subsequent propagation of the flame in a duct, illustrated in Figure 2-5, is even more dangerous than if the duct were unprotected by a screen, because now the punctured screen flame arrester acts as a flow obstruction to the burned gas and causes a higher flame speed. The effect of constricting the outlet opening is illustrated by Wilson and Crowley's (References 2-2 and 2-3) use of a constricting orifice on a duct outlet to promote high flame speeds in their flame arrester tests. A flow obstruction on a duct outlet was used to obtain deflagration-to-detonation transition during some detonation-flame arrester tests at the Jet Propulsion Laboratory (Reference 2-10).

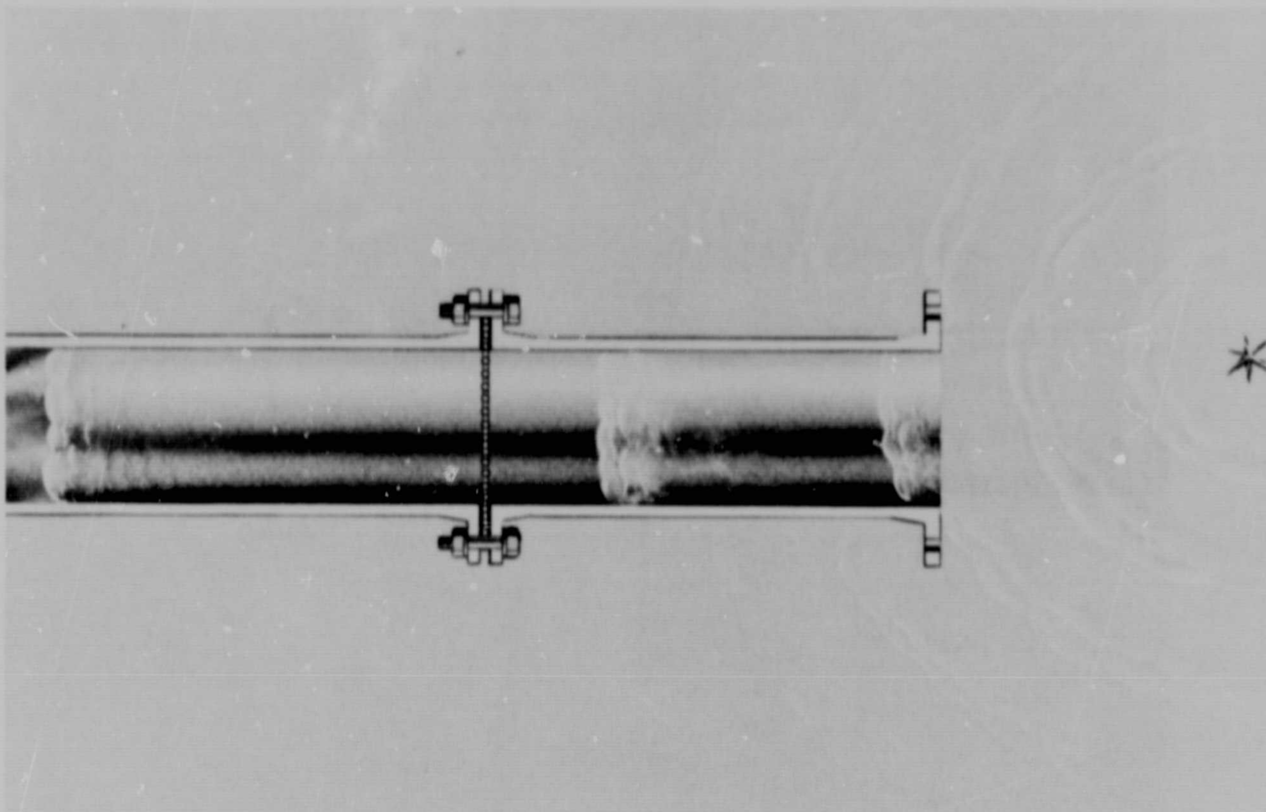


Figure 2-4. An Internally Mounted Screen Flame Arrester is Penetrated by an Accelerating Flame in the Vent Stack Piping

Some basic properties useful in carrying out the experimental work reported herein are listed for convenient reference. In Table 2-1, the fuel's most common name, the chemical name (International Union of Chemistry nomenclature), chemical formula, and molecular weight are listed. Some of these fuels possess other common or trade names in commerce, but the listed names should be adequate to identify the material completely.

In Table 2-2, basic flame properties are listed (Reference 2-12). The stoichiometric air/fuel ratio is the minimum mass of air needed to burn the fuel to carbon dioxide and water. The laminar burning velocity is the maximum value reported for the fuel burning in air at 25°C and one atmosphere of pressure. The equivalence ratio (defined as the ratio of the stoichiometric air/fuel ratio to the actual air/fuel ratio) at which the maximum burning velocity is observed is tabulated next. The critical diameter for flame quenching is reported for two

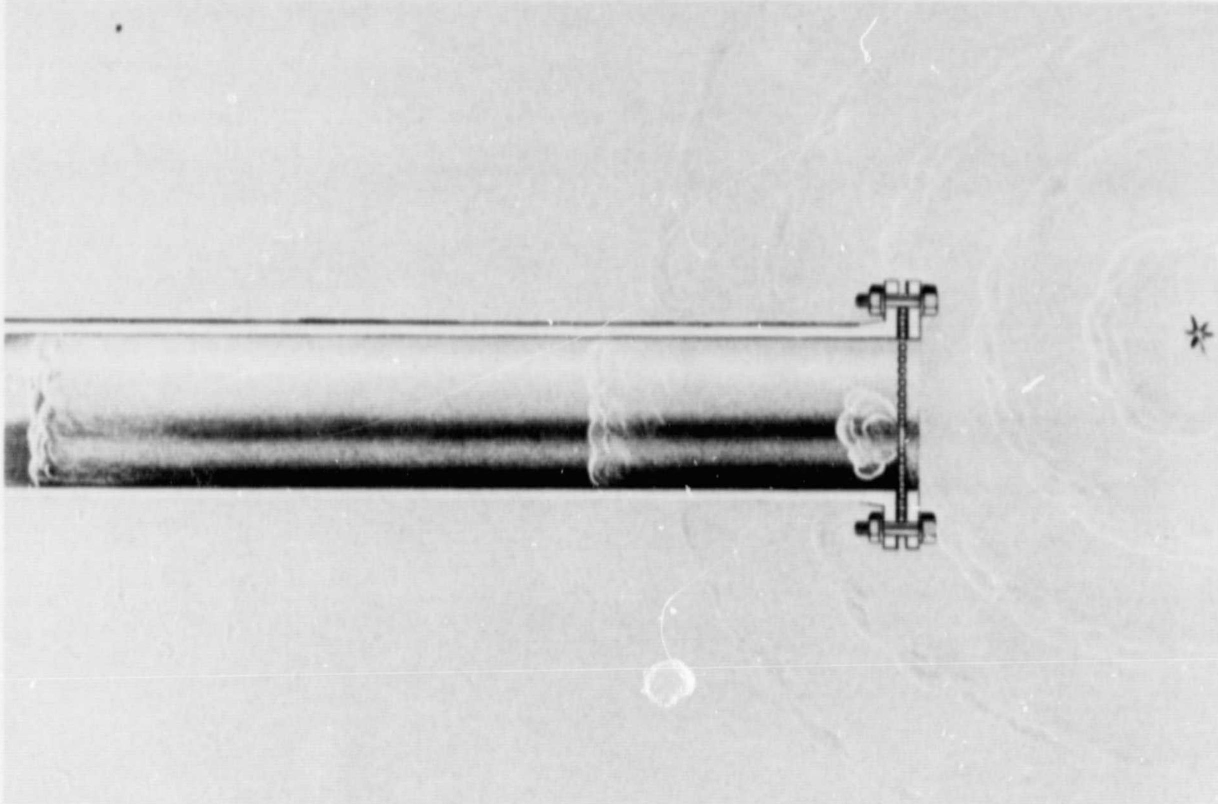


Figure 2-5. A Propagating Flame Penetrates a Damaged Screen Flame Arrester and Accelerates in the Piping

conditions: the first is at stoichiometric air/fuel ratio, and the second is at the minimum of the quenching diameter—equivalence ratio curve. For all practical purposes, the equivalence ratio for minimum quenching diameter coincides with the equivalence ratio for maximum burning velocity. The spontaneous ignition temperature as determined in an ASTM test is given. The equivalence ratio for the lean flammability limit for upward propagation in a closed tube is listed. These values are lower than the flammability limit for downward propagation, hence are more conservative for estimating conditions for ignition in the flame arrester tests. Reported values are under temperature conditions where fuel-vapor/air mixtures can be obtained, and one atmosphere pressure.

Table 2-1. Properties of Selected Fuels

Common Name	Chemical Name	Formula	Molecular Weight
Acetaldehyde	Ethanal	CH_3CHO	44.053
Butane	n-Butane	C_4H_{10}	58.123
Diethyl ether	Ethoxy ethane	$(C_2H_5)_2O$	74.122
Ethylene	Ethene	C_2H_4	28.054
Gasoline	—	$C_8H_{15.44}$	111.44
Methyl alcohol	Methanol	CH_3OH	32.042
Propane	Propane	C_3H_8	44.096
Toluene	Methyl benzene	$C_6H_5CH_3$	92.140

Table 2-2. Combustion Properties of Selected Test Fuels

Fuel	Stoichiometric[a] ($\phi = 1.0$) Air/Fuel Mass Ratio	Laminar[b] Burning Velocity, cm/s	Equivalence Ratio = (ϕ) at Maximum Burning Velocity	Quenching Diameter of Tube, cm		Spontaneous Ignition Temperature, °C (°F)	Lean Flammability Limit for Upward Propagation in a Closed Tube ϕ
				Stoichiometric	Minimum		
Acetaldehyde	7.85	(50)[c]	(1.15)[c]	0.35	----[d]	175 (347)	0.50
Butane	15.46	45	1.13	0.46	0.28	430 (807)	0.54
Diethyl ether	11.19	47	1.15	0.38	0.31	186 (366)	0.55
Ethylene	14.79	81	1.15	0.20	----	490 (914)	0.41
Gasoline	14.62	40 to 42	1.10	----	----	371 (700)	0.60
Methyl alcohol	6.47	56	1.01	0.28	0.23	470 (878)	0.48
Propane	15.68	46	1.14	0.31	0.28	504 (940)	0.51
Toluene	13.50	41	1.05	----	----	468 (1054)	0.43

[a]Composition of air: N_2, 78.087; O_2, 20.946; CO_2, 0.033; Ar, 0.934, in volume percent.

[b]At one atmosphere, 25°C mixture.

[c]Estimates.

[d]Data not available.

SECTION III

TEST FACILITY DESCRIPTION

A. GENERAL

All testing for this program was performed at the B-Stand facility of the Jet Propulsion Laboratory's Edwards Test Station. The B-Stand test area contains an air compressor system, fuel system, fuel vaporizer and condenser loop, fuel and air induction system, facility piping, test flame chamber, and an exhaust-burn stack. The test facility flow system schematic diagrams are shown in Figures 3-1 and 3-2. Table 3-1 gives a description of the symbols used in the schematic diagrams. A detailed description of the major portion of this test facility is given in Reference 2-10. Some modifications and additions were made to incorporate gaseous-type fuels, flashback flame testing, and sustained burning testing for this program.

The following is a brief description of the various facility systems including the modifications and new additions.

B. AIR COMPRESSOR SYSTEM

A new multistage centrifugal turbine air compressor was installed, which is rated for 11.3 m^3/min (400 indicated cfm) at 41.4 kN/m^2 (6.0 psid). It is driven by a 14.9-kW (20-hp) electrical motor. Air flow in the 10.2-cm- (4-in.-) diameter pipe system is controlled by a remotely operated metering valve and a remotely operated bypass valve. Flow rate is measured using a Meriam Laminar Flow Element (LFE).

C. FUEL SYSTEM

Two parallel systems provide a variety of either liquid or gaseous fuels. Liquid fuel was supplied by a nitrogen gas pressurized tank with a capacity of 0.049 m^3 (13 gal) and a working pressure of 6895 kN/m^2 (1000 psia). Fuel flow was controlled by a remotely operated metering valve and measured with a turbine-type flowmeter. Gaseous fuel was supplied from a manifold containing two type-1A shipping cylinders having the combined volume of 0.0876 m^3 (3.08 ft^3). The normal delivery pressure was 8274 kN/m^2 (1200 psia). Gas flow was controlled by a remotely operated pressure regulator and measured with a precision-bored sonic orifice. The fuel gas temperature was stabilized for flow measurement using a water bath preheater.

D. FUEL VAPORIZER AND CONDENSER LOOP

All fuels were either vaporized or preheated with a remotely regulated electrical heat exchanger before injection into the flowing air stream. A pneumatically operated three-way valve energized to the RUN position directed the heated fuel into the fuel injection manifold. With the valve in the CONDENSER position, the heated fuel was directed into a water bath heat exchanger where most of the

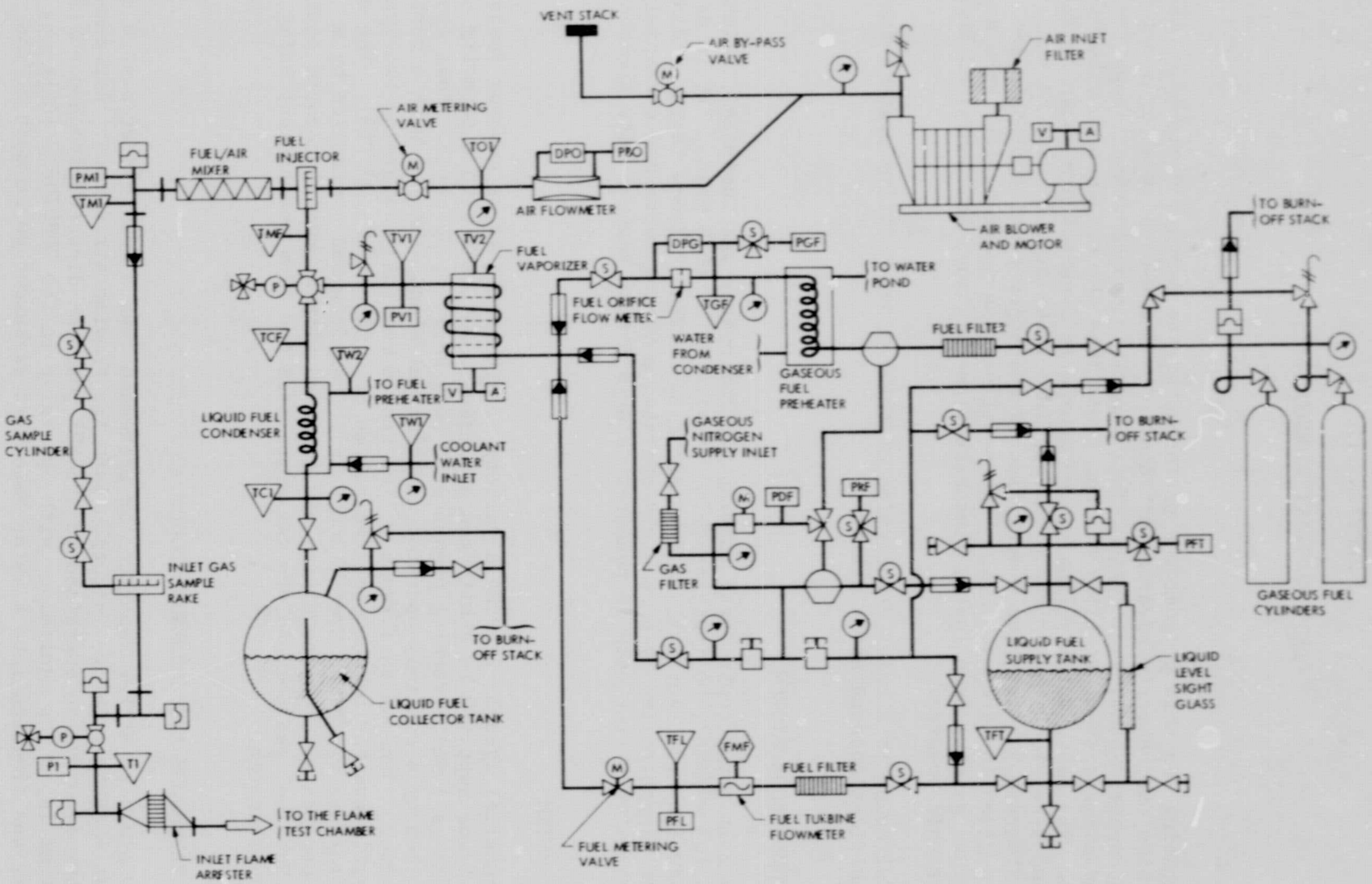


Figure 3-1. Test Facility Fuel and Air Systems Schematic Diagram with Instrumentation Locations for Flame Arrester Testing

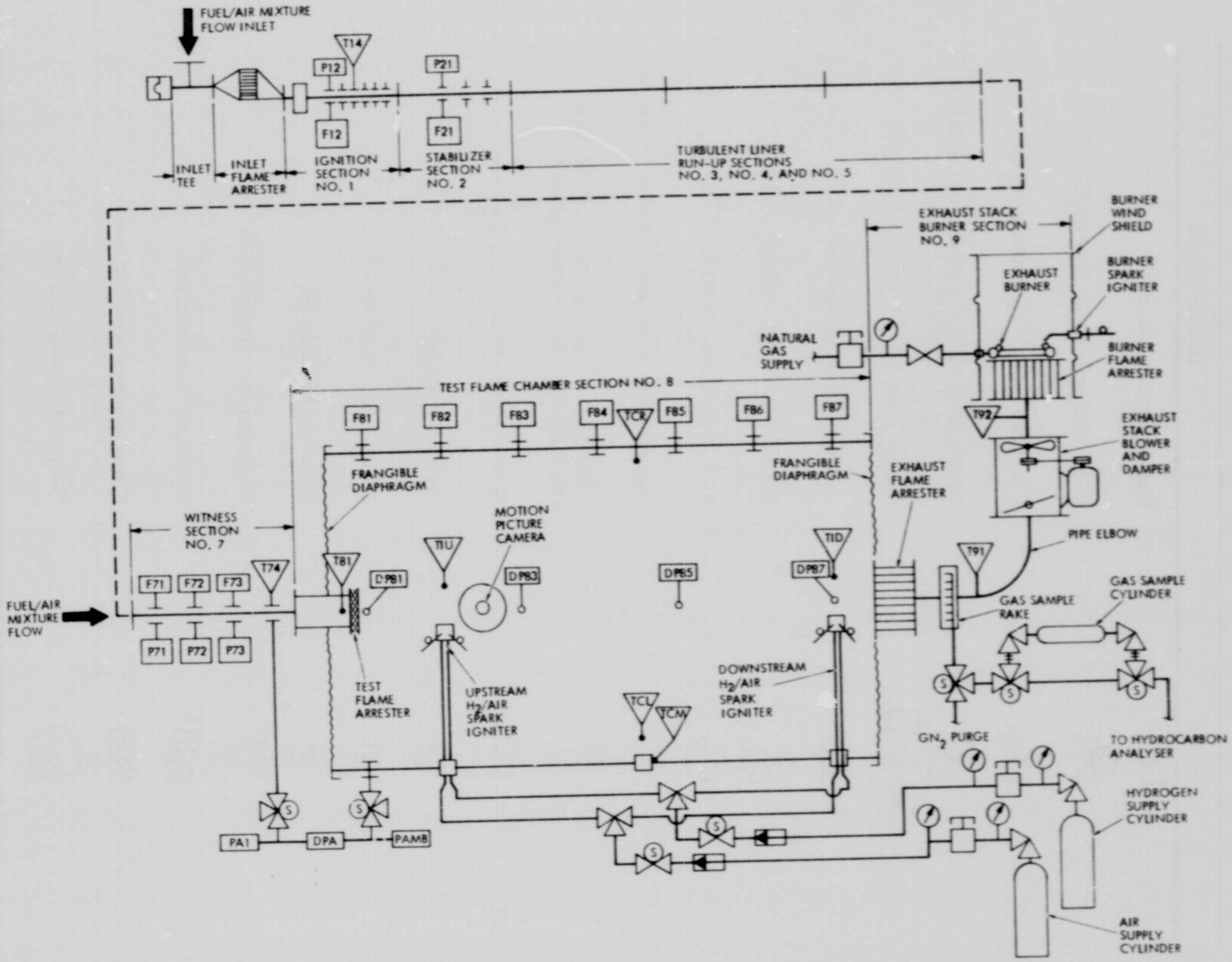
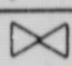
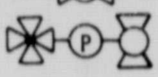


Figure 3-2. Flashback Flame Test Chamber Flow System Schematic Diagram with Instrumentation Locations for Flame Arrester Testing

Table 3-1. Symbols and Descriptions for Flow System Schematic Diagram

Symbol	Description
	Manual globe valve
	Electric solenoid operated valve
	Electric motor operated valve
	Electric motor operated ball valve
	Air piston operated ball valve
	One-way flow check valve
	Pressure relief safety valve
	Dome pressure regulator valve
	Manual set pressure regulator valve
	Electric motor operated pressure regulator valve (dome loader)
	Pressure rupture disc assembly
	Pressure gage
$\boxed{V}$	Voltmeter transducer
$\boxed{A}$	Ammeter transducer
TXX	Temperature transducer
$\boxed{PXX}$	Pressure transducer
$\boxed{FXX}$	Flame sensor transducer
FXX	Flowmeter transducer

vaporized fuels were reliquified and collected in a storage tank. The noncondensable fuels were vented through the collector tank to a burn stack for disposal.

E. FUEL AND AIR INDUCTION SYSTEM

Fuel was injected into the air stream through a seven-tube manifold in the 10.2-cm- (4-in.-) diameter piping. A four-element Komax motionless mixer induced turbulent mixing of the fuel/air mixture. Four low-pressure rupture discs and a one-way flow check valve in the piping provided protection against unavoidable back pressure spikes caused by flame flashbacks in the facility piping. A photograph of the combined air, fuel, vaporizer, condenser, and induction system is given in Figure 3-3.

F. FACILITY PIPING

The fuel/air mixture was delivered to the test section through 23.8 m (78 ft) of extra-strong 15.2-cm- (6-in.-) diameter piping. A detailed description of various sections of this piping is given in Reference 2-10. Briefly, the facility piping contains instrumentation ports for mounting temperature, pressure, and optical flame-sensing transducers. The inlet end of this piping is securely mounted into a thrust butt to withstand any pipe line detonations. There is a high-pressure pipe transition section in the inlet that houses a spiral-wound, crimped stainless-steel ribbon arrester. This arrester quenches any propagating flames or detonations that penetrate into the facility piping from the test section. The hydrogen/air spark igniter was removed from the inlet ignition section

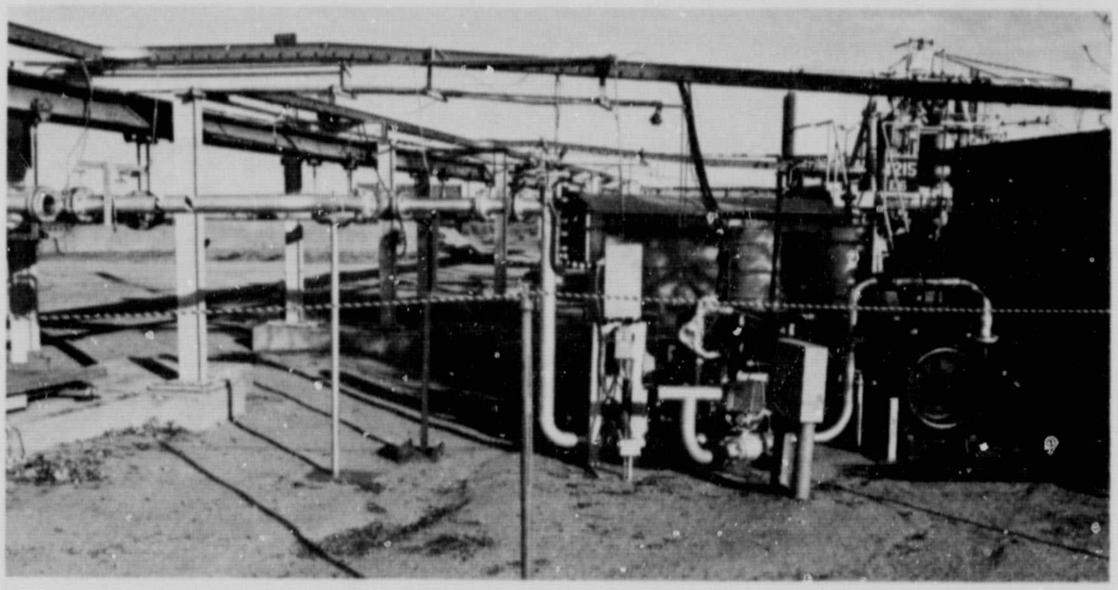


Figure 3-3. Combined Air, Fuel, Vaporizer, Condenser, and Induction Systems on B-Stand

and relocated to the new flame test chamber at the exit end of the facility piping. The witness section and the pipe mounting adaptors for the flashback flame arresters were located at the entrance to the flame chamber. The flame sensors and pressure sensors shown in Figure 3-4 were mounted in the witness section to record penetration of the flame through the test arresters.

G. FLAME TEST CHAMBER

The flashback flame tests were performed in a new test chamber that was fabricated and installed on B-Stand facility as shown in Figure 3-5. The chamber is a horizontal length of galvanized, corrugated pipe, 2.44 m (96 in.) in outside diameter, 4.27 m (14 ft.) in length, and 4.3 mm (0.168 in.) thick, with 6.78- × 1.27-cm (2.67- × 0.50-in.) helical corrugations. The open ends of the chamber were reinforced by welding on rolled angle rings, 5.1 × 5.1 × 0.64 cm (2 × 2 × 1/4 in.). Additional rolled angle rings covered with black polyethylene sheeting,

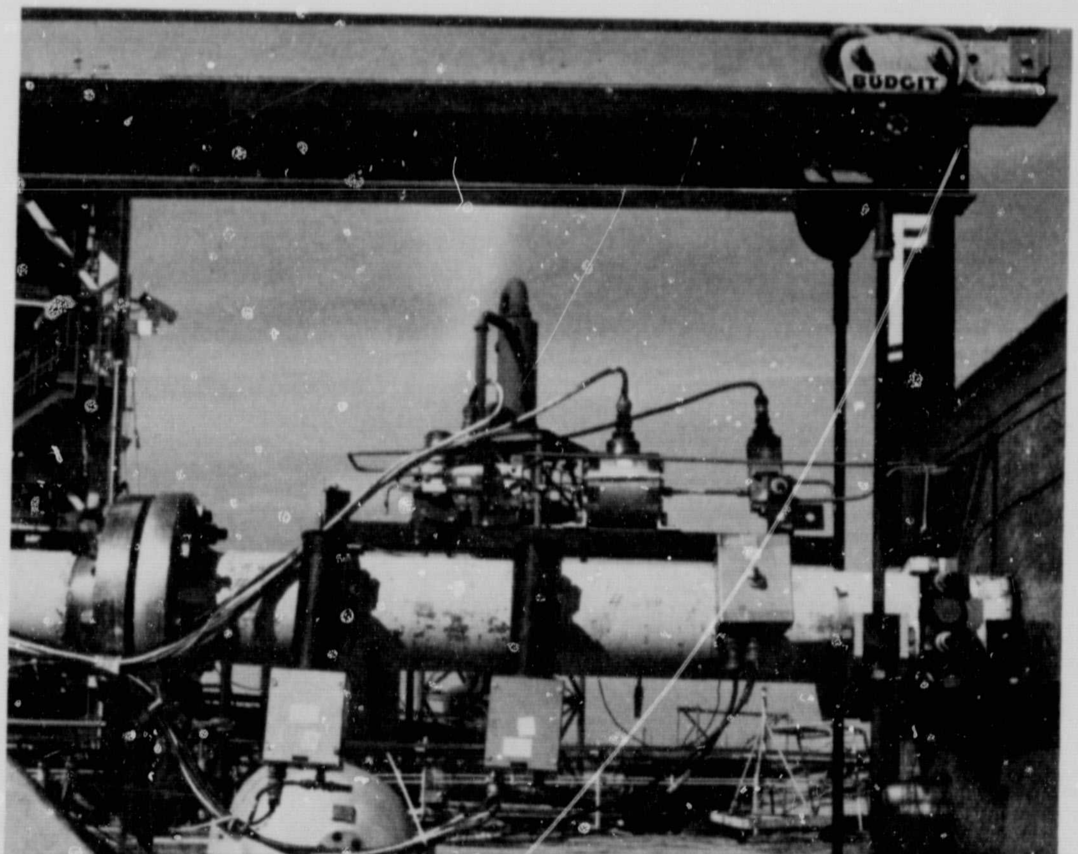


Figure 3-4. Flame Sensors and Pressure Sensors Mounted on the Witness Section Piping

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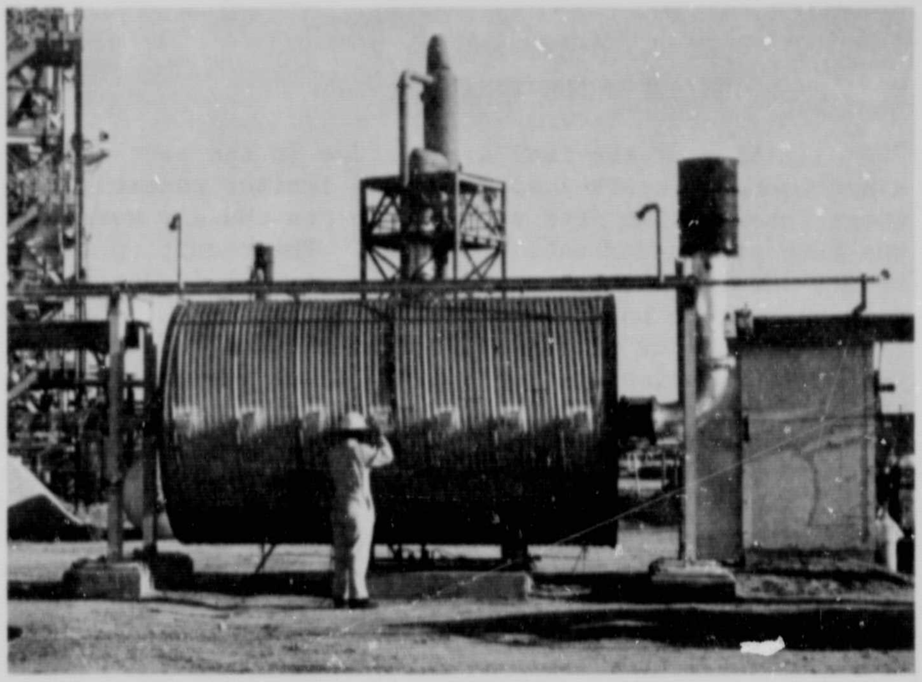

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Figure 3-5. Full-Scale Flame Test Chamber Installed on B-Stand

0.15 mm (0.006 in.) thick and banded into place, were used as frangible diaphragms to close the open chamber ends. This served two purposes: the dark environment enhanced motion picture photography of the flame front, and the closed chamber eliminated dispersion of the fuel/air mixture that might have been caused by local winds. Once the mixture in the chamber was ignited, the heat and increased pressure from the burning mixture blew out the diaphragms.

The interior surface of the chamber was painted flat black to aid photography. A glass viewing port near the upstream end of the chamber was used to take motion pictures of flame propagation. Reference light ports in the wall opposite the camera were used to indicate distances along the flame path. Instrumentation in the test chamber included four pressure sensors mounted, equispaced, on the wall along the horizontal center line. Seven flame sensors were originally mounted, equispaced, along the horizontal center line opposite the pressure sensors. However, early in the program, the flame sensors were relocated to the top center line of the chamber for a better viewing position of the stratified flame front. Five thermocouples were used to measure gas temperatures within the chamber. Locations of the pressure, temperature, and flame sensors are shown in the schematic drawing Figure 3-2.

H. HYDROGEN/AIR SPARK IGNITER

Ignition of the fuel/air mixture in the test chamber was accomplished with a hydrogen/air spark igniter. This igniter resembled a small rocket engine, where intersecting jets of hydrogen gas and air were ignited by a spark plug in the base of the combustion chamber. The resulting flame was directed vertically upward through a short nozzle for a nominal duration of 200 ms. The igniter assemblies were built into the end of a 1.1-m- (3.5-ft.-) long section of 5.08-cm- (2-in.-) diameter pipe mounted into fittings on the bottom of the test chamber. The point location of the ignition flame was just below the axial centerline of the chamber. There were three possible locations for the igniters: (1) upstream near the test arrester, (2) midchamber, and (3) downstream at the chamber exit. Only the upstream and downstream igniter position were used during the test program. When the downstream igniter position was used, the frangible diaphragm on the chamber exit was shielded from the flame by a sheet of aluminum covering approximately 40% of the total exit area. The aluminum shield delayed the rupture of this diaphragm until the flame had traversed the length of the chamber to reach the test arrester on the inlet end. This delay made it possible to obtain good quality motion pictures of the flame impinging on the arrester before the chamber was exposed to ambient light through the ruptured diaphragms. A photograph of the downstream igniter and flame shield are shown in Figure 3-6.

I. EXHAUST-BURN STACK

An exhaust-burn stack was required for this test facility in compliance with air pollution regulations covering the controlled release of hydrocarbon vapors. This was accomplished by installing a 1.22-m (4-ft.) length of 30.5-cm (12-in.) diameter piping on a vertically directed pipe elbow at the exit end of the flame chamber. The pipe contained a ducted fan and damper valve to control the exhaust flow, which, in turn, maintained atmospheric pressure in the test chamber prior to ignition. Spiral-wound, crimped metal ribbon arresters were attached to both ends of the exhaust stack assembly to prevent the propagation of flame into the piping. A gas sample rake was installed just downstream of the inlet flame arrester. The fuel/air mixture sample taken at this location was fed into an on-line total hydrocarbon analyser. The sample line was closed by a solenoid operated valve just prior to ignition to protect the analyser. At the top of the vertical stack, a shielded natural gas fired burner disposed of all combustible exhaust products. A photograph of the exhaust-burn stack assembly and the frangible diaphragm at the exit of the flame chamber is shown in Figure 3-7.

J. SUSTAINED BURNING TEST FACILITY

The facility piping was modified after completion of the flame chamber testing to relocate the flame arrester test assembly out to an open area for the sustained burning tests. Two pipe elbows were inserted just upstream of the witness section to lower and turn the piping 90 deg away from the supporting structure. Another pipe elbow was inserted between the downstream end of the witness section and the arrester test assembly; this elbow directed the exhaust flow vertically up as shown in Figure 3-8. The gas sample rake for the hydrocarbon analyser was inserted between the flanges upstream of the test section. Ignition was

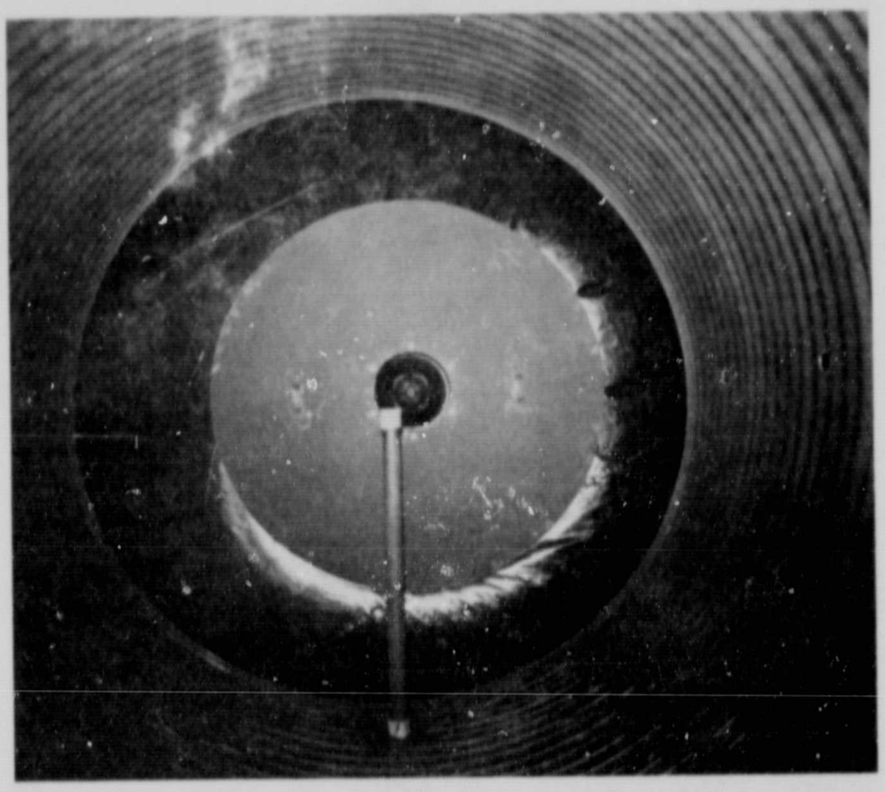

Figure 3-6. Downstream Location of the Hydrogen/Air Spark Igniter and Flame Shield

accomplished by a spark electrode mounted on the downstream face of the test flame arrester. Thermocouples were installed at various locations in the test assembly to measure the extent of thermal soak-back from the sustained flame at the surface of the arrester. A motion picture camera and a television camera were set up to record and monitor the arrester conditions during testing.

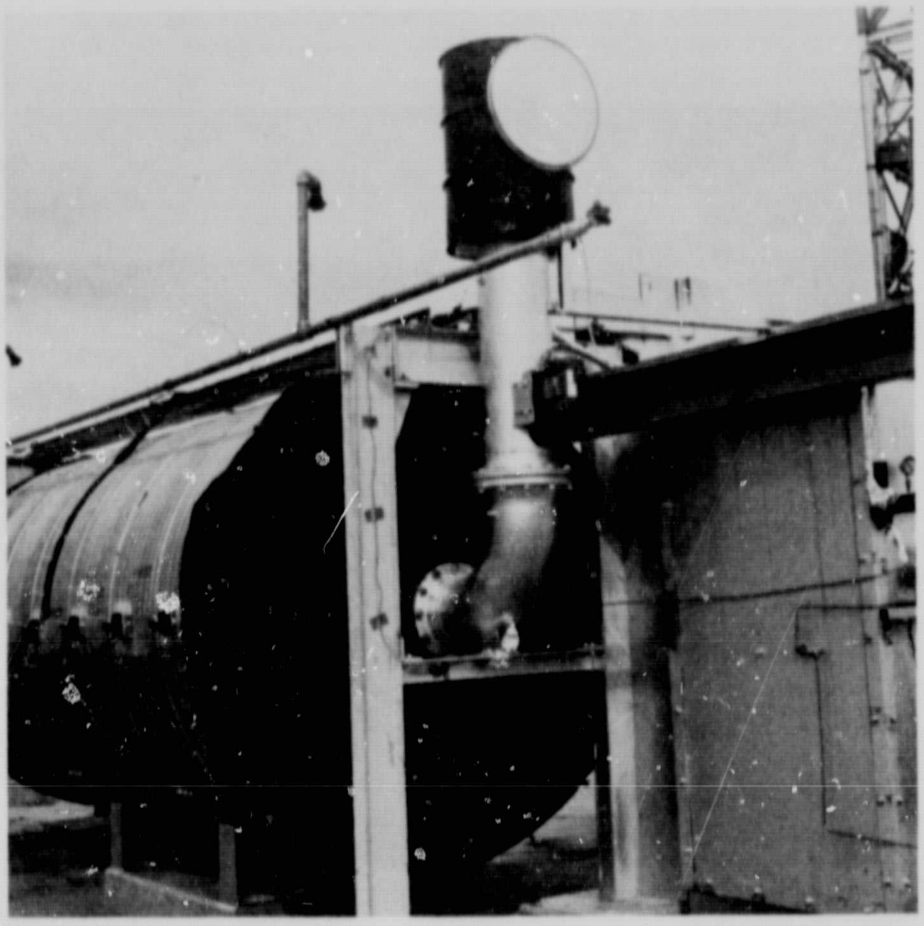

Figure 3-7. Exhaust-Burn Stack Assembly and Frangible Diaphragm at Flame Test Chamber Exit

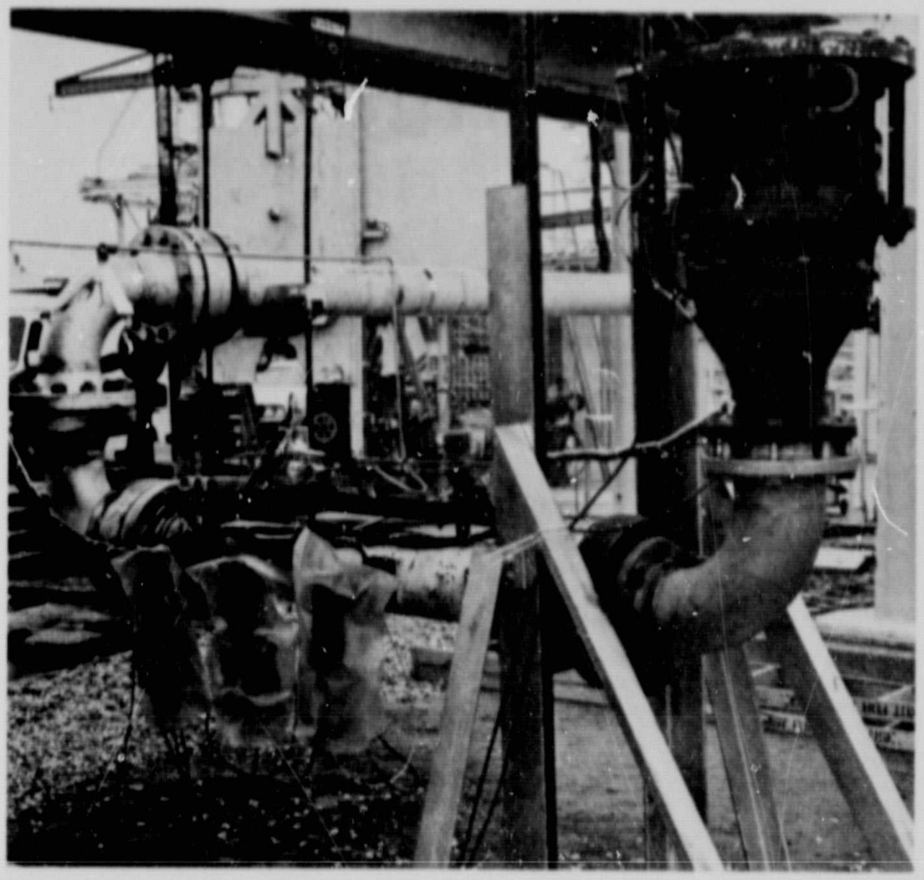

Figure 3-8. Sustained Burning Arrester Assembly Test Facility

SECTION IV

INSTRUMENTATION AND CONTROLS

A. GENERAL DESCRIPTION

All instrumentation and controls at B-Stand facility were remotely operated and monitored. Test system parameters were measured at the test site using electrical transducers with their signals conducted to the blockhouse for conditioning, recording, and display. Location and identification of all principal instrumentation parameters and controls are shown in Figures 3-1 and 3-2. Table 4-1 is a listing of the nomenclature for all instrumentation and calculated parameters.

Test system parameters were divided into two groups: (1) steady-state (low-speed), and (2) transient-state (high-speed) data. Steady-state data includes all the measured and calculated parameters for the air system, fuel system, fuel vaporizer and condenser loop, fuel/air induction system, hydrocarbon analyser, and the pre- and posttest pressure loss measured across the test arrester. Transient-state data includes the measured and calculated flame speeds and peak pressures developed in the test flame chamber and facility piping, and the success or failure of the experimental flame arrester.

Steady-state data was recorded and calculated on the JPL-developed Integrated Digital Acquisition and Controls System (IDAC) with back-up by the new Edwards Digital Acquisition and Control System (EDAC). Transient-state data was recorded on two high-frequency FM tape recorders and played back on an oscillograph at an expanded time scale. Flame speeds and peak pressures were manually scaled and calculated from the oscillograph traces. Flame speeds in the test chamber were also estimated from the high-speed motion picture films.

All critical control functions were either manually positioned on the controls console or automatically operated by the preset sequence timer. These operations were selectively recorded using electrical contact closures on IDAC, EDAC, FM tape, or a second high-speed oscillograph. Two strategically placed television (TV) cameras, with video displays in the blockhouse, monitored the fuels system area and the test flame chamber. Two high-speed motion picture cameras also recorded events both inside and outside the test flame chamber during the actual test firings. Visual coverage and controlled access to the test area were maintained by a safety monitor in an observation tower located over the blockhouse.

A detailed description of the instrumentation and controls system is given in Reference 2-10. Modifications and new additions that were made to the systems for this test program are described in the following paragraphs.

B. STEADY-STATE DATA

The EDAC system is a new digital instrument recently installed at ETS. It was still in the process of functional checkout at the time of this program, so it was used as a backup steady-state data computing and recording system for the

Table 4-1. Instrumentation and Calculated Test Parameter Nomenclature

Steady-State Parameters	Units, S.I. (Engr.)	Description
PBO	kN/m^2 (psig)	Air flowmeter inlet pressure
DPO	kN/m^2 (psid)	Air flowmeter differential pressure
TO1	°C (°F)	Air flowmeter temperature
PFT	kN/m^2 (psig)	Fuel tank pressure
TFT	°C (°F)	Fuel tank temperature
PDF	kN/m^2 (psig)	Fuel tank dome loader pressure
PFL	kN/m^2 (psig)	Fuel line pressure
TFL	°C (°F)	Fuel line temperature
FMF	Hz (cps)	Fuel flowmeter frequency
PGF	kN/m^2 (psig)	Gaseous fuel pressure
DPG	kN/m^2 (psid)	Gaseous fuel differential pressure
TGF	°C (°F)	Gaseous fuel temperature
PV1	kN/m^2 (psig)	Fuel vaporizer outlet pressure
TV1	°C (°F)	Fuel vaporizer outlet temperature
TV2	°C (°F)	Fuel vaporizer core temperature
TMF	°C (°F)	Fuel injector inlet temperature
PM1	kN/m^2 (psig)	Fuel/air mixer outlet pressure
TM1	°C (°F)	Fuel/air mixer outlet temperature
TCF	°C (°F)	Fuel condenser inlet temperature
TC1	°C (°F)	Fuel condenser outlet temperature
TW1	°C (°F)	Coolant water inlet temperature
TW2	°C (°F)	Coolant water outlet temperature
P1	kN/m^2 (psig)	Inlet tee pressure
T1	°C (°F)	Inlet tee temperature
P12	kN/m^2 (psig)	Inlet section pressure
P21	kN/m^2 (psig)	Stabilizer section pressure
P71	kN/m^2 (psig)	Witness section inlet pressure
P72	kN/m^2 (psig)	Witness section center pressure
P73	kN/m^2 (psig)	Witness section exit pressure
F12	s (sec)	Inlet section flame sensor
F21	s (sec)	Stabilizer section flame sensor
F71	s (sec)	Witness section inlet flame sensor
F72	s (sec)	Witness section center flame sensor
F73	s (sec)	Witness section exit flame sensor
DP81	kN/m^2 (psid)	Flame chamber differential pressure, Sta. 1
DP83	kN/m^2 (psid)	Flame chamber differential pressure, Sta. 3
DP85	kN/m^2 (psid)	Flame chamber differential pressure, Sta. 5
DP87	kN/m^2 (psid)	Flame chamber differential pressure, Sta. 7
F81	s (sec)	Flame chamber flame sensor, Sta. 1
F82	s (sec)	Flame chamber flame sensor, Sta. 2
F83	s (sec)	Flame chamber flame sensor, Sta. 3
F84	s (sec)	Flame chamber flame sensor, Sta. 4
F85	s (sec)	Flame chamber flame sensor, Sta. 5
F86	s (sec)	Flame chamber flame sensor, Sta. 6
F87	s (sec)	Flame chamber flame sensor, Sta. 7

Table 4-1. Instrumentation and Calculated Test Parameter Nomenclature (Continuation 1)

Steady-State Parameters	Units, S.I. (Engr.)	Description
T74	°C (°F)	Witness section exit temperature
T81	°C (°F)	Test arrester inlet temperature
TIU	°C (°F)	Upstream igniter flame temperature
TID	°C (°F)	Downstream igniter flame temperature
TCR	°C (°F)	Flame chamber roof temperature
TCL	°C (°F)	Flame chamber lower temperature
TCM	°C (°F)	Flame chamber metal temperature
T91	°C (°F)	Exhaust stack inlet temperature
T92	°C (°F)	Exhaust stack exit temperature
HCA	%	Exhaust stack total hydrocarbon analysis
PA1	kN/m^2 (psig)	Test arrester inlet pressure
DPA1	kN/m^2 (psid)	Test arrester differential pressure-pretest
DPA2	kN/m^2 (psid)	Test arrester differential pressure-posttest
PAMB	kN/m^2 (psia)	Test area ambient pressure
Calculated Parameters	**Units, S.I. (Engr.)**	**Description**
MA	kg/h (lb/h)	Air mass flow
MF	kg/h (lb/h)	Liquid fuel mass flow
A/F	ratio	Air mass flow to liquid fuel mass flow ratio
MFG	kg/h (lb/h)	Gaseous fuel mass flow
A/FG	ratio	Air mass flow to gaseous fuel mass flow ratio
ϕ	ratio	Equivalence ratio
VA	m/s (ft/sec)	Air flow velocity through 15.2-cm (6.0-in.-) diameter pipe
FXX-FYY	m/s (ft/sec)	Average flame speed between two adjacent flame sensors
SX-SY	m/s (ft/sec)	Average flame speed between two adjacent light ports or a light port and the test arrester obtained from the motion pictures

older IDAC system, which it will eventually replace. The heart of the EDAC is a Data General Nova 3D computer. It has a maximum recording rate up to 20,000 channels per second. At this time only 120 channels are assigned to the B-Stand facility.

During the calibration sequence, EDAC records the counts each calibration point for the assigned channel and then uses those counts, along with the appropriate reduction equation, to calculate the engineering units for each parameter. The computer also performs calculations such as averaging, polynomials, and general form equations involving two or more input channels. Other recording capabilities include totalizers, period counters, parallel data, and contact closure time tagged to the nearest millisecond.

EDAC outputs data on magnetic tape, line printers, and video monitors. The magnetic tapes are used for record storage, from which posttest playbacks of input parameters and calculations are made to the line printer. The line printer records 10 parameters with channel identification, engineering units, and time. Time editing is programmable for maximum output at points of interest. The video monitors provide on-line real-time displays of up to 10 parameters with channel identification, engineering units, and contact closure status. These displays can be selected from 6 preprogrammed pages. High and low limits can be assigned to input parameters. The limit output signal is capable of operating control circuits or sounding alarms within 10 milliseconds of exceeding a limit.

Simultaneous steady-state data from both the IDAC and EDAC systems were very comparable, although not exactly alike. This discrepancy is reportedly caused by a basic difference in the time base for computer calculation between the two systems that cannot be resolved. The EDAC system when totally operational will replace IDAC as the primary data system for follow-on programs.

C. TRANSIENT-STATE DATA

New flame sensors that could withstand repeated exposure to ambient light and still remain sensitive to the light-blue color of hydrocarbon flame had to be assembled for the flashback flame chamber. The Du Mont Type 6291 photomultiplier tubes used as flame sensors in the facility piping were not suitable because the phosphorescent coating on the detector can be deteriorated by bright sunlight. Photovoltaic type detectors, similar to those reported in Reference 2-3 which do not have this sensitivity, were used instead. They are the EG and G Model HUV-1000B silicon photovoltaic detectors that have a spectral range from 2000 Å to 11500 Å (200 to 1150 Nm) with a maximum response at 9000 Å (900 Nm) and a responsivity of 12×10^7 volts/watt. Operational amplifiers were built to the specifications and circuitry suggested by EG and G. The detector and amplifier were assembled in a weather-tight aluminum box with a phototube viewing port containing a single front collimating slot. The distance from the collimating slot to the detector could be varied to optimize the viewing angle and detector signal strength. Although the rise-time response of the photovoltaic detector is somewhat slower than the photomultiplier tube, 1.5 microseconds compared to 50 nanoseconds, it is more than adequate for detecting the expanding atmospheric flame front in the flame chamber.

Seven photovoltaic flame sensors were initially installed at 0.61-m (2-ft) intervals along the horizontal centerline of the flame chamber. They were later relocated to the chamber top centerline when motion pictures of flame propagation showed the flame illumination intensity varying unpredictably from top to bottom in the chamber. It is believed this is caused by gravitational stratification of the fuel/air mixture after it leaves the facility piping. The flame detector's overhead view, looking down into the propagating flame front, resulted in more reliable flame speed measurements.

Flame chamber peak pressure rise was measured with four Statham Model PM 5 TC differential pressure-type transducers mounted at 1.22-m (4-ft) intervals along the horizontal centerline of the chamber. It was intended that these pressure sensors measure the pressure rise at the chamber wall during the passage of the flame front. In actual practice, they simultaneously sensed the rise in chamber pressure from the spherically expanding ball of flame up to the point of chamber diaphragm rupture. The resulting resonance from this pressure spike in the chamber masked any evidence of flame passage past the individual pressure sensors.

Three flame sensors and three pressure sensors mounted at 0.31-m (1-ft) intervals on opposite sides of the witness section piping were used to record flashback flame penetration through the test arresters. Two of these flame sensors were a photomultiplier tube type and one was a photovoltaic type. The pressure sensors were all quartz-crystal piezoelectric-type transducers flush-mounted to the inside wall. In addition, there was a similar combination of flame sensor and pressure sensor in both the inlet igniter section and stabilizer section of the facility piping to record flame propagation up to these locations. An inlet flame arrester stopped any further flame penetration beyond this point into the induction system piping.

The signals from all flame sensors and pressure sensors located in the flame chamber and facility piping were recorded on two high-frequency FM tape recorders and the on-line oscillograph. A 100-Hz coded time pulse and the spark igniter current were also recorded and used as reference points for test initiation and time correlation between the various recorders. A typical example of transient-state data for the flame chamber sensors recorded on the FM tape and playback on an oscillograph with an expanded time base is shown in Figure 4-1.

The EDAC system was used as the principal recorder for the thermal soak-back data measured by thermocouples installed on the flame arresters during sustained burning tests. Recorded at millisecond scan intervals, the data was time edited, played back, and printed at time intervals ranging from 5 to 120 seconds, depending on the length of test and the transient-state of the data. Video displays of this real-time flame arrester temperature data were monitored during the test to identify flame penetration. This was later confirmed by data from the flame sensors and pressure sensors in the witness section piping that was recorded on FM magnetic tape and played back on the oscillograph.

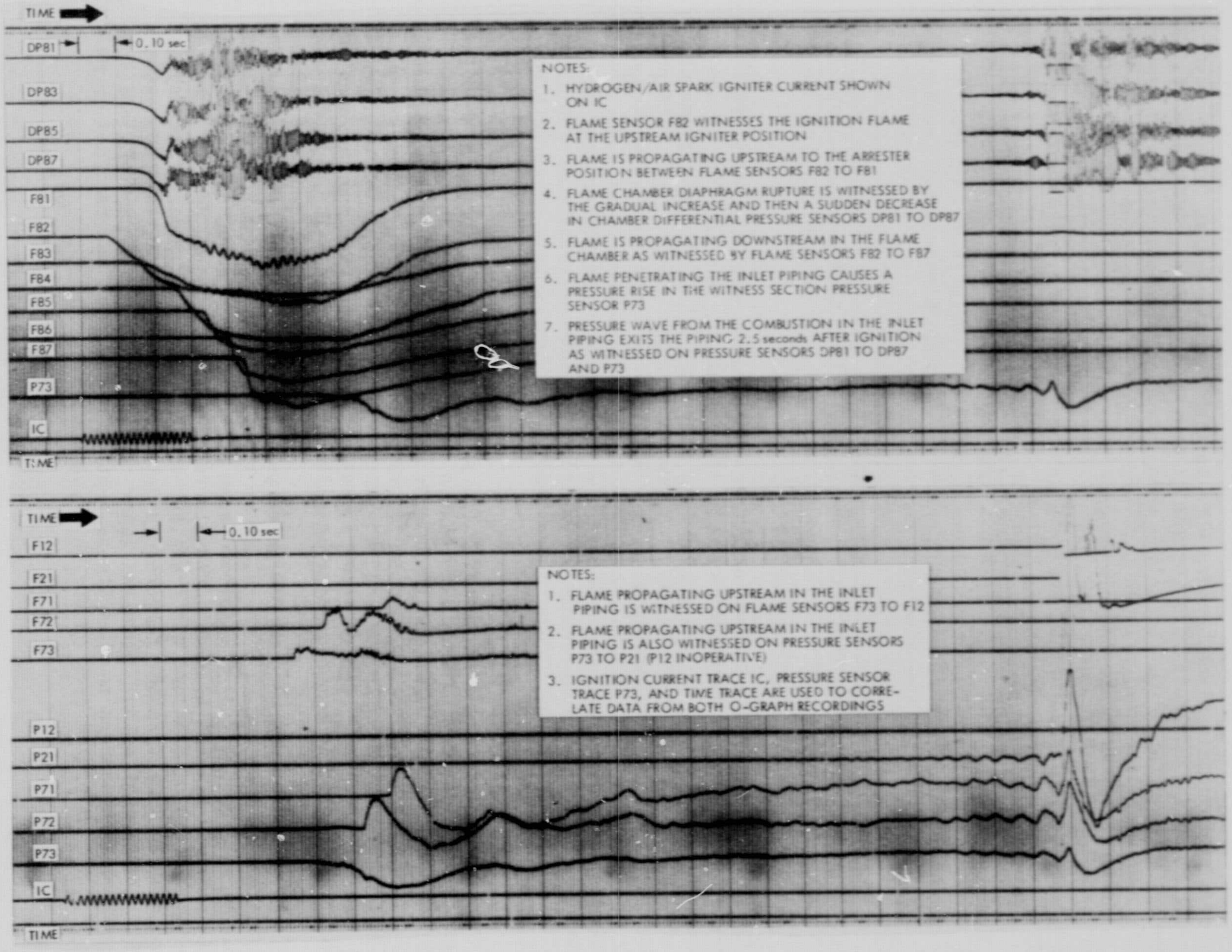

Figure 4-1. Typical Example of Transient-State Data Recorded on FM Tape and Played Back on an Oscillograph

D. GAS-SAMPLE ANALYSIS SYSTEM

The gas-sample analysis system used for this program is described in detail in Reference 2-10. Briefly, it is an on-line system that utilizes a Beckman Model 400 Total Hydrocarbon Analyser instrument combined with a JPL designed and fabricated air dilution and calibration system. The analyser automatically and continuously measures the concentration of hydrocarbon in a flowing gas sample, utilizing the flame ionization method of detection. It was calibrated using propane (C_3H_8) and air mixtures. To analyse other hydrocarbon fuel and air mixtures, the number of carbon atoms per molecule of fuel had to be in a ratio to that of propane. A flow system schematic drawing of the complete gas-sample analysis system is shown in Figure 4-2. A listing of the fuels and their properties that are used in this program is given in Tables 2-1 and 2-2.

The hydrocarbon gas analyser was located as close to the test flame chamber as practical to minimize response time. It was placed in a steel-walled protective enclosure adjacent to the exhaust-burn stack. The gas sample rake was installed in the inlet elbow of the exhaust-burn stack. A three-way solenoid valve provided a gaseous nitrogen purge through the sample rake when not in use. Analyser response time after activation of the three-way sample valve was approximately 30 seconds. Figure 3-7 is a photograph of the protective enclosure housing the gas analyser located next to the exhaust-burn stack.

E. PHOTOGRAPHIC DATA

Two motion picture cameras were used to record every test firing. One camera was positioned outside the flame chamber with a view of the entire test section assembly. Operating at 32 frames per second, this camera recorded the rupture of the flame chamber diaphragms and the extent of the emitted flame plume. The other camera was positioned adjacent to the flame chamber observation window with a view of the inside of the chamber, including the upstream igniter and the downstream face of the test arrester. Figure 4-3 is a photograph of this camera installation. Operating at 100 frames per second, it was possible with this camera to record the propagating flame front inside the chamber. Four light ports, equally spaced on the opposite wall, provided reference points for determining distance traveled. A schematic drawing of the flame-chamber camera installation is shown in Figure 4-4. The distances traveled by an expanding spherical flame, when viewed by the camera, are indicated between each adjacent light port, and from the light port in line with the igniter to the face of each of the four flame arrester test assemblies. By counting the number of motion picture frames required for the flame front to traverse these known path lengths, the lapse time was estimated and the average flame speed was calculated. The flame speeds obtained by this method will not necessarily agree with those calculated from the flame sensor data, because of the different sight locations and viewing angles, but they are of the same order of magnitude. Figure 4-5 is a selected series of six photographs taken from test motion picture film showing a toluene/air flame propagation from ignition to sustention on the downstream face of the dual 20-mesh screens arrester. Figure 4-6 is a similar series of photographs showing a toluene/air flame propagation from ignition to penetration into the open ended facility piping, causing an eruption of flame from the pipe.

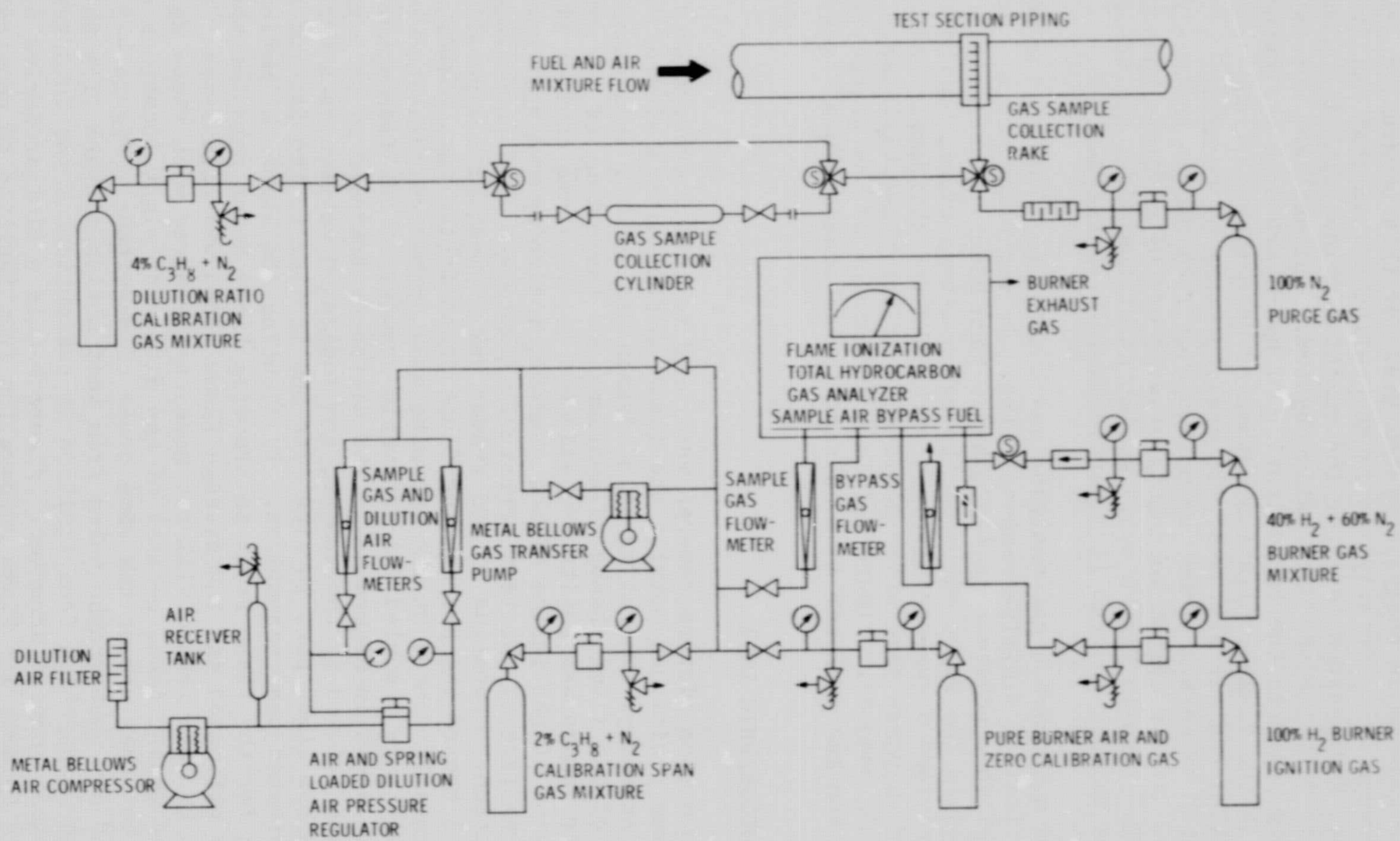

Figure 4-2. Hydrocarbon Gas Sample Analyser and Air Dilution Flow System Schematic Diagram

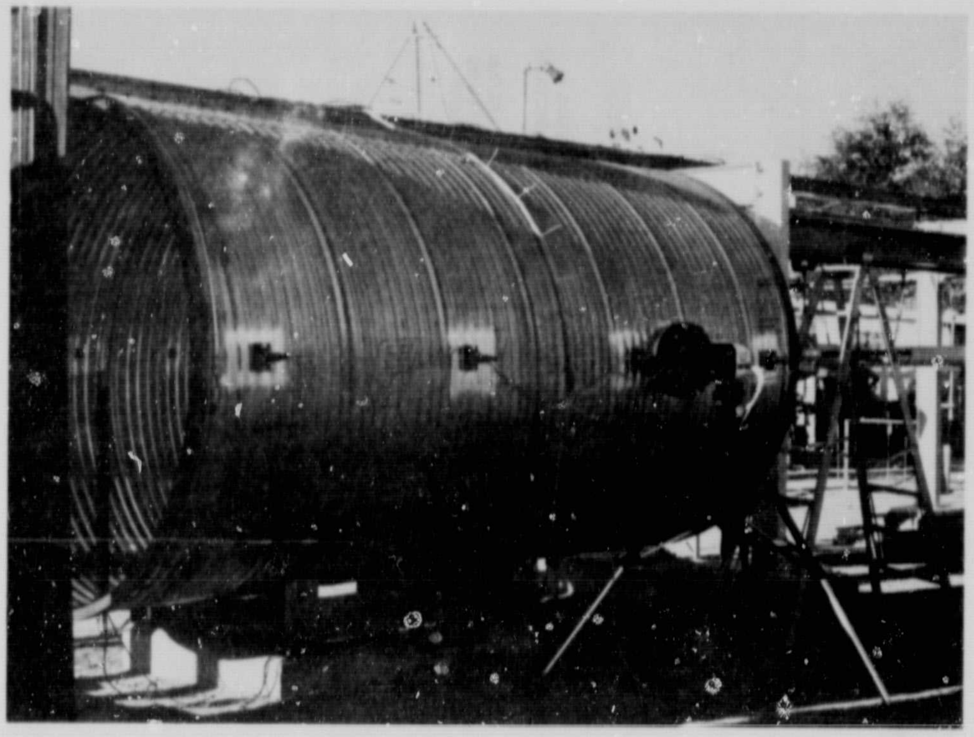

Figure 4-3. Flame Test Chamber Motion Picture Camera Installation

F. PARAMETER MEASUREMENT AND CALCULATION UNCERTAINTIES

The IDAC system was the primary recorder for steady-state data, with back-up by the EDAC digital system. These systems have computer capability that converts input data to engineering units, and outputs it on printers and video monitors. Special IDAC and EDAC software programs were written for air and fuel systems data to calculate air-mass flow, fuel-mass flow, air-to-fuel ratio, and equivalence ratio. To get maximum accuracy from the instrumentation systems, an end-to-end calibration method is employed. A detailed description of the instrumentation systems, calibration methods, and the determination of uncertainty for measured and calculated parameters is presented in Reference 2-10. The following is a summary of the IDAC steady-state data uncertainties assured with a 95% (2σ) probability.

(1) Uncertainty for pressure measurement is ±0.39% of transducer full-scale range.

(2) Uncertainty for differential pressure measurement is ±0.58% of transducer full-scale range.

(3) Uncertainty for temperature measurement in percent of reading is:

(a) 10.0 to 31.8°C (50 to 100°F) = ± 2.7%

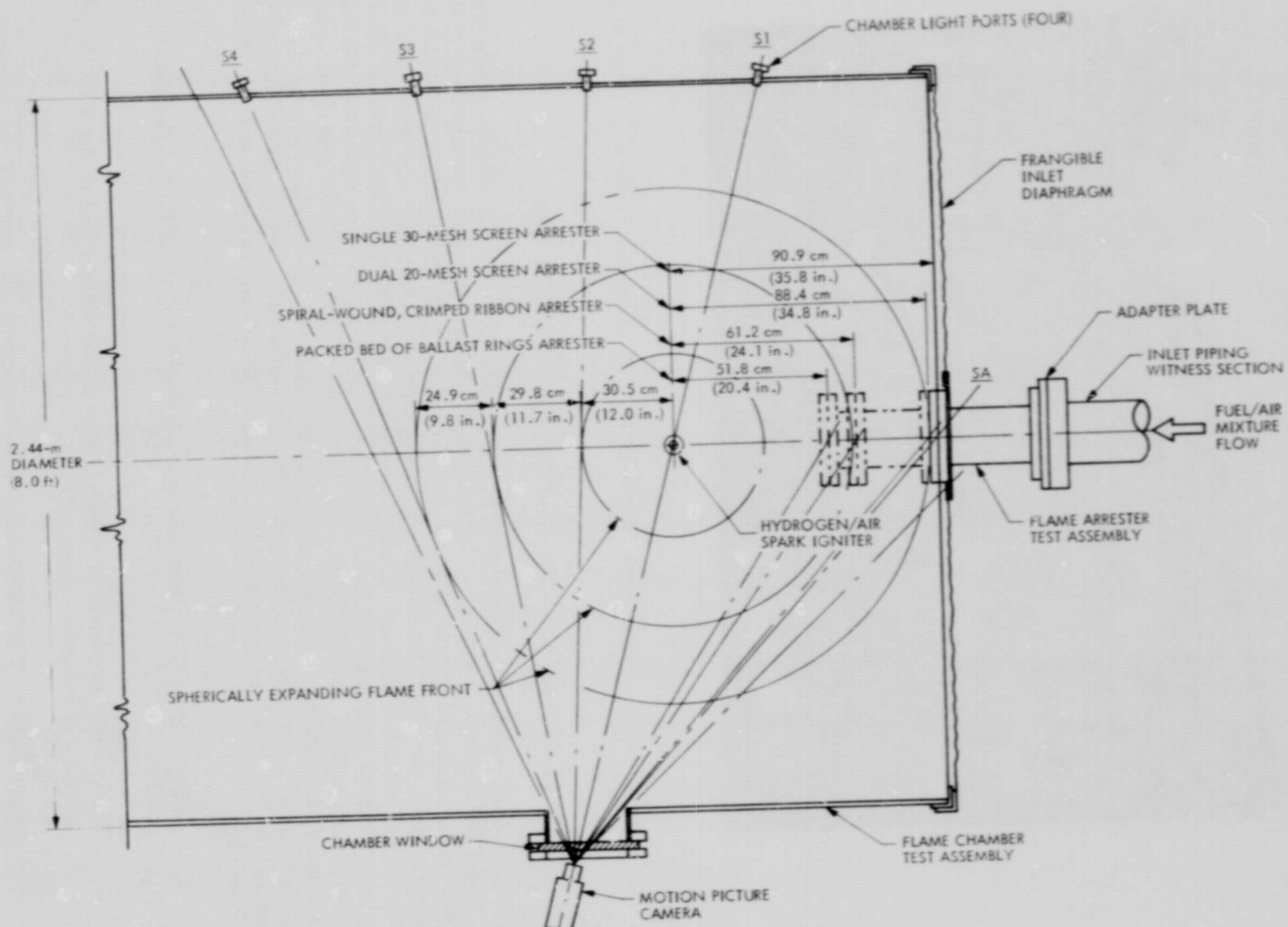

Figure 4-4. Schematic Drawing of Flame Test Chamber Motion Picture Camera Installation

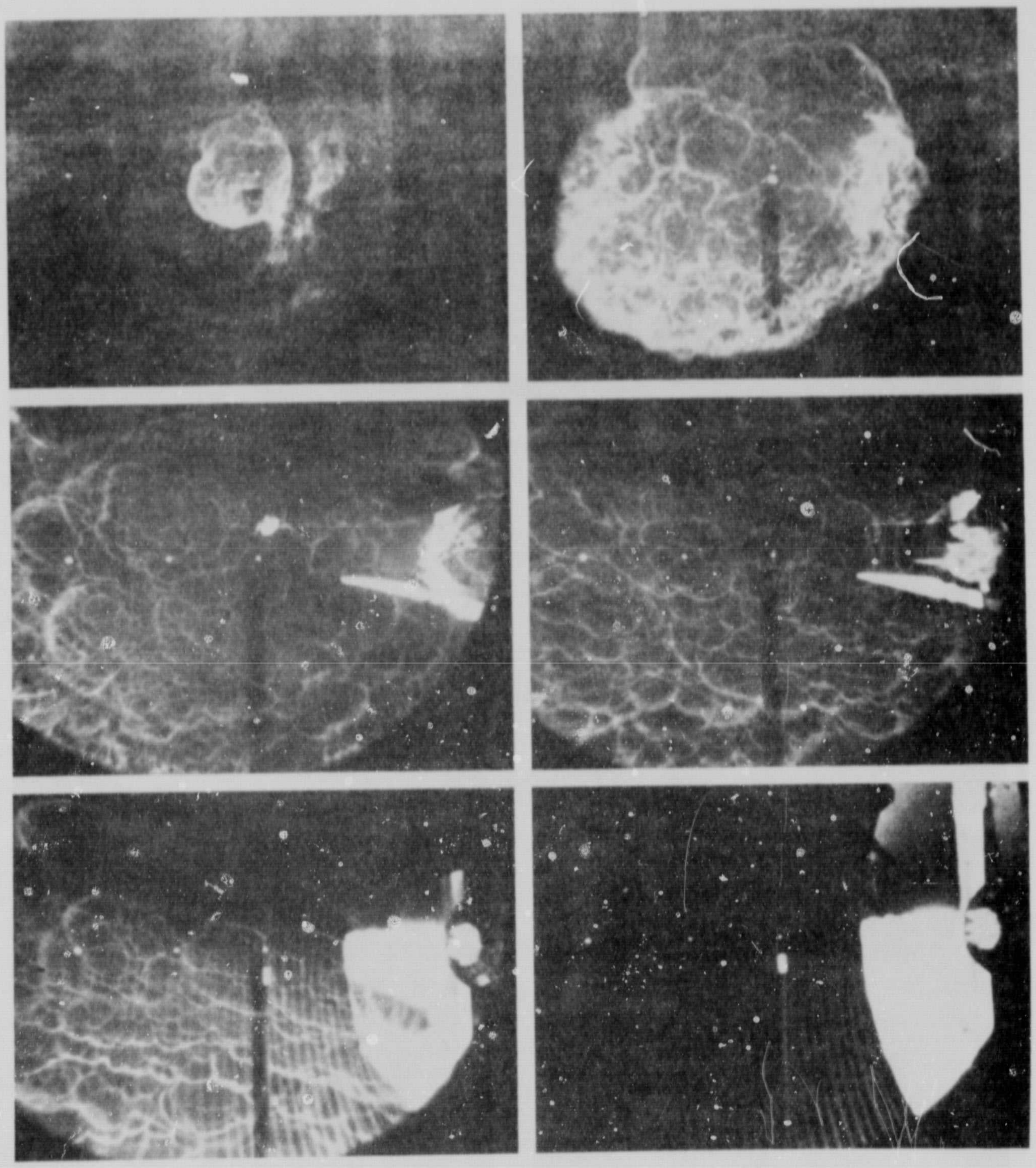

Figure 4-5. Toluene/Air Mixture Flame Propagation From Ignition to Sustention on Dual 20-Mesh Screen Arrester

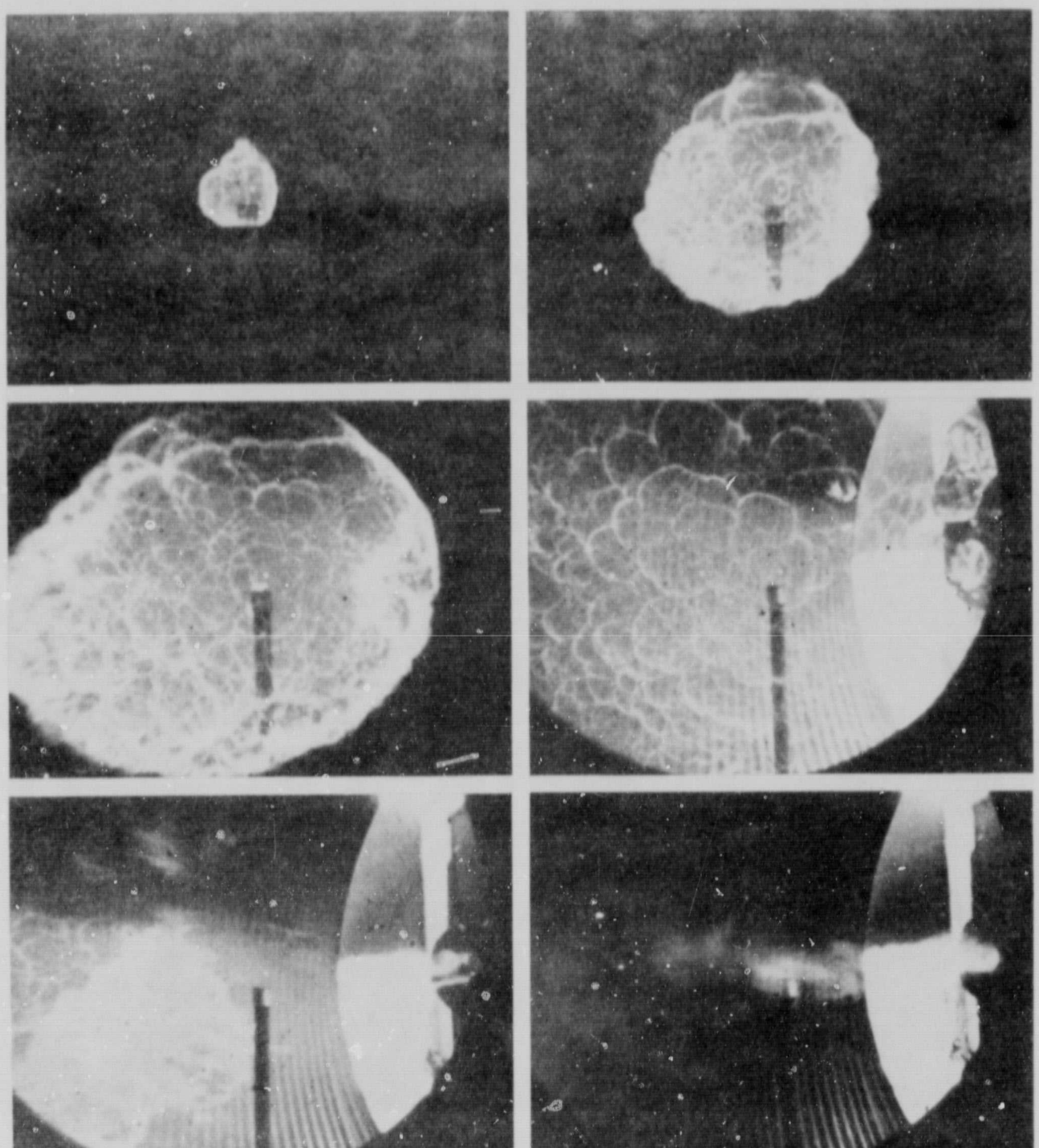

Figure 4-6. Toluene/Air Mixture Flame Propagation From Ignition to Penetration into the Open Ended Facility Piping

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(b) 37.8 to 93.3°C (100 to 200°F) = ± 1.4%
(c) 93.7 to 148.9°C (200 to 300°F) = ± 0.85%
(d) 148.9 to 204.4°C (300 to 400°F) = ± 0.65%
(e) 204.4 to 276.7°C (400 to 530°F) = ± 0.49%
(f) 276.7 to 1260°C (530 to 2300°F) = ± 0.43%

(4) Uncertainty for air-velocty or air-mass-flow calculations is ±1.82% of value.

(5) Uncertainty for liquid-fuel-mass-flow calculation is ±1.93% of value.

(6) Uncertainty for gaseous-fuel-mass-flow calculation is ±2.88% of value.

(7) Uncertainty for calculated air-to-liquid-fuel mixture ratio and equivalence ratio is ±2.65% of value.

(8) Uncertainty for calculated air-to-gaseous-fuel mixture ratio and equivalence ratio is ±3.41%.

Using the uncertainties listed above, the maximum uncertainty that can be expected for the measured and calculated steady-state test parameters associated with the average value at standard test conditions are listed in Table 4-2.

The transient-state data were recorded on an Ampex Model FR 2200 and an Ampex Model FR 3020 high-frequency FM tape recorders. Photovoltaic detector flame sensors were the primary instruments used to determine flame speeds. Strain-gauge-type differential pressure transducers were the primary instruments used to measure peak pressure rise in the flame chamber. Flame sensor and pressure sensor test data, along with pre- and posttest calibrations recorded on the FM tapes, were played back on an oscillograph at an expanded time base. The following is an analysis of the uncertainties associated with transient-state data assured with a 95% (2σ) probability.

(1) The uncertainty of flame chamber peak-pressure rise measurement is ±5.85% of transducer range.

(2) The uncertainty of calculated flame sensor flame speed measurement is ±5.45% of value.

(3) The uncertainty of calculated photographic flame speed measurement is ±10.07% of value.

The maximum uncertainty that can be expected for measured and calculated parameters associated with the averaged values of flashback flame speed and peak pressure rise in the test flame chamber at standard test conditions are listed in Table 4-2.

Table 4-2. Maximum Uncertainty for Measured and Calculated Parameters at the Standard Test Condition

Parameter	Symbol	Uncertainty
Steady-State Data		
Air flowmeter inlet pressure	PBO	±0.27 kN/m^2 (±0.039 psig)
Air flowmeter differential pressure	DPO	±0.0083 kN/m^2 (±0.0012 ps)
Air flowmeter exit temperature	T01	±1.3°C (±2.8°F)
Liquid fuel line pressure	PFL	±14.0 kN/m^2 (±2.0 psig)
Liquid fuel line temperature	TFL	±0.9°C (±2.7°F)
Liquid fuel flowmeter frequency	FMF	±0.8 Hz
Gaseous fuel line pressure	PGF	±17.2 kN/m^2 (±2.50 psig)
Gaseous fuel line temperature	TGF	±0.9°C (±2.7°F)
Test arrester inlet pressure	PA1	±0.269 kN/m^2 (±0.039 psig)
Test arrester differential pressure	DPA	±8.3 N/m^2 (±0.0012 psid)
Test area ambient pressure	PAMB	±0.538 kN/m^2 (±0.078 psia)
Air-mass flow	MA	±1.90 kg/h (±4.19 lb/h)
Air velocity	VA	±0.083 m/s (±0.27 ft/s)
Liquid-fuel-mass flow	MF	±0.158 kg/h (±0.35 lb/h)
Air to liquid-fuel-mass ratio	A/F	±0.35
Gaseous-fuel-mass flow	MFG	±0.240 kg/h (±0.529 lb/h)
Air to gaseous-fuel-mass ratio	A/FG	±0.44
Equivalence ratio	ϕ	±0.04
Transient-State Data		
Flame chamber peak pressure rise	DPXX	±121 N/m^2 (±0.0176 psid)
Flame sensor flame speed	FXX-FYY	±0.19 m/s (±0.63 ft/s)
Photographic flame speed	SX-SY	±0.35 m/s (±1.16 ft/s)

SECTION V

TEST OPERATING PROCEDURES

A. GENERAL SAFETY REQUIREMENTS

All test operating procedures involving fuel transfer, or performed with the fuel system pressurized, required the safety tower operator to be in position, monitor all communication on a headset, and control access to the test area with the safety status lights. The test stand was normally in a GREEN condition, which permitted open access to all personnel. Fuel transfers and test preparations were performed in an AMBER condition, which restricted nonoperating personnel to the workshop area, unless permission was granted to enter other areas. A RED condition, which isolated the test stand and the surrounding designated area from all personnel, was used during actual test.

A minimum of two men was required at the site during fuel transfers and test preparations. Personnel safety equipment included hard hats, face shields, gloves, fire retardant coveralls, and for some fuels, breathing air systems. Additional safety equipment was available including safety showers, eye washes, and the Firex water deluge system. All operations, except the replacement of the flame chamber diaphragms and the changing of the test flame arrester, were performed using formal procedures in the form of check lists, with individual pages dated and timed, and with each step initialed by two persons witnessing the event.

An ignition-completion key switch, which prevented the actuation of the hydrogen/air spark igniter except during checkouts and test operations, was located at the test stand.

B. OPERATING PROCEDURE CHECK LISTS

The following is a description of the operating procedures and check lists used in the flashback flame tests.

1. Pretest System Checkouts

a. Preliminary Check. This check confirmed proper installation of the test item, instrumentation and control cable connections, readiness of the nitrogen pressurant and purge system, selection of the proper fuel supply mode, requested photographic coverage, and that the safety system was operational.

b. Electromechanical Checkouts. These checks examined, at the test stand, the overall control system readiness by individual confirmation of proper operation of each control in the blockhouse.

c. Sequence Timer/Emergency Circuit Checkout. This checkout operated the preset automatic sequence timer, without actual fuel flow, while recording control-element actuations on the facility oscillograph. Sequence times of the various elements were measured and adjusted where necessary. The sequence was then repeated, adding a shutdown with the emergency switch to confirm proper emergency switch actuations.

d. Leak Check. These checks provided a gaseous nitrogen system leak check at maximum operating pressure for the fuel system, fuel vaporizer and condenser loop, fuel induction system, and the air compressor system.

NOTE: The four checklist procedures described above were not performed before each test, but were done when special circumstances, such as component changes, malfunctions, or severe weather, were encountered.

2. Fuel Transfer Procedures

a. Propellant (fuel) Fill Check Lists. These procedures were provided for transferring liquid fuels from their storage containers into the test stand fuel supply tank. Propane and butane were transferred via their own vapor pressure. The other liquid fuels were transferred from drums by means of an air-motor-driven pump. It was common to expect up to five separate tests in a day, each of which required approximately 4.6×10^{-3} m^3 (1 gal) of fuel. Therefore, the fuel supply tank was topped off for each test day. The gaseous fuel system was loaded by simply connecting new pressurized gas cylinders to the supply manifold.

b. Propellant (fuel) Offload. These transfers from the fuel supply tank were normally returned to the appropriate storage container. Small quantities of propane or butane could also be disposed of through the burn stack. Generally, fuels from the vaporizer/condenser loop remaining in the collector tank were not suitable for recycling and were disposed of as waste. It was necessary to empty the collector tank after every two days of testing.

3. Test Preparations

The Test Preparations Check Lists for instrumentation and test systems were completed concurrently on the day of testing. In the blockhouse, all patchboard connections were completed and instrumentation was setup. An end-to-end instrumentation system calibration was performed. At the test stand, various safety check and facility setups were made: condenser cooling water was turned on, the hydrocarbon analyzer was put in operation, and the hydrogen and air gas pressures were adjusted for the igniter. At the control console, the air compressor was started and the air flow adjusted by means of the air metering valve and the air bypass valve. After the air system temperature and flow were stabilized at the desired values, the test flame arrester pretest pressure loss was measured and recorded.

The fuel vaporizer heater was activated, and nitrogen purge gas flowed through the heater coils and into the condenser for the preheat cycle. The test stand safety condition was changed from GREEN to AMBER. The fuel supply tank was pressurized with nitrogen up to the desired operating pressure. The vaporizer heater nitrogen purge gas was turned off and fuel flow was metered at a low level. The fuel flow was increased up to the desired test condition as the vaporizer heater reached the operating temperature.

Final visual checks were made of the test stand area, and the ignition completion key switch was turned on. All operating personnel evacuated the test stand area and its safety condition was changed to RED.

4. Blockhouse Preparation

Blockhouse preparation began with a weather station confirmation of wind velocity and direction and the local barometric pressure. Control console circuits for ignition and emergency shutdown functions were armed and each significant panel switch and its position confirmed. With all test personnel at their operating positions, the test conditions were reviewed and confirmed. A pretest instrumentation calibration was recorded and the countdown procedure was begun.

5. Countdown

A typical "countdown" procedure follows:

(1) An announcement was made over the public address system to alert personnel in the general area that a detonation may occur. Generally, the detonation noise was very intense and sharp, capable of creating an indirect hazard. A horn signal was also sounded.

(2) The IDAC tape, EDAC tape, printer, and oscillograph were turned ON to a SLOW SPEED.

(3) The hydrocarbon analyzer purge was turned OFF, allowing the analyzer to sample the fuel/air mixture flowing through the exhaust-burn stack.

(4) The fuel mixer valve was changed to the RUN position, allowing fuel to flow to the test piping for the first time in the test sequence. The burn-stack-purge valve was opened to sweep out combustible gases from the collector tank vent line. The oscillograph was turned OFF.

(5) As the fuel/air mixture traveled through the facility piping and into the flame chamber, the hydrocarbon analyzer responded with a steadily increasing signal. The countdown timer was then stopped for a HOLD period, while fuel flow and air flow were confirmed or adjusted, if necessary. During flame chamber testing, the time required for the mixture ratio of chamber exhaust gas to reach the desired level ranged from 2 to 27 minutes due to differences in chamber temperature, fuel density, and flow-through characteristics in the test chamber.

(6) When the COUNTDOWN was resumed, the IDAC tape, EDAC tape, and printer were switched to CONTINUOUS MODE and the oscillograph and movie camera were turned ON. The vaporizer heater was turned OFF (flame chamber tests only) to prevent electrical switching noise on the data traces during the test. The high-frequency FM tape recorder was turned ON.

(7) The hydrocarbon analyzer purge was turned ON, again isolating it from the test system to protect it from possible pressure pulse damage.

(8) Valves were actuated to the CLOSED position to isolate the low-pressure transducer from possible pressure pulse damage.

(9) The igniter was ARMED by a console switch and the oscillograph was switched to HIGH SPEED.

(10) The sequence timer was turned ON. This caused the igniter to fire for 300 ms. For flame chamber tests, the hydrogen and air valves for the igniter were opened and the transformer energizing the spark plug was powered simultaneously. Actual duration of the flame was 150 to 200 ms. For sustained burning tests, only the transformer energizing the spark electrode igniter was powered for 300 ms.

(11) At the end of the desired test time, the test was terminated by operating the EMERGENCY CUTOFF switch. For flame chamber tests, this occurred five seconds after ignition. For sustained burning tests, this occurred thirty minutes after ignition or when flame penetration occurred. The EMERGENCY CUTOFF switch triggered the following events: fuel mixer valve was switched from RUN to CONDENSE position, vaporizer purge was turned ON, vaporizer heater was turned OFF (sustained burning tests only), fuel tank outlet valve (liquid) was CLOSED, and fuel cylinder outlet valve (gaseous) was CLOSED.

(12) The igniter was UNARMED, the oscillograph changed to LOW SPEED, and the high-frequency tape turned OFF.

(13) The fuel metering valve was CLOSED and the movie camera was turned OFF.

(14) Fuel supply tank pressure transducers were vented and a posttest calibrate was performed on the instrumentation.

(15) Fuel supply tank pressure transducers and the test arrester pressure transducers were reopened to the test system and all instrumentation was turned OFF.

(16) Compressor air flow was maintained to purge residual fuel and combustion by-products from the test piping.

6. Posttest

The posttest procedure included a visual inspection of the test stand. The test stand safety condition was changed to AMBER. Reentering personnel inspected all rupture disc assemblies, and replaced discs as required. The posttest flame arrester pressure loss was measured and recorded. Chamber diaphragms were replaced for repeats of flame chamber tests.

If a repeat test was to be made, the hydrocarbon analyzer was checked out. The Test Preparation Procedure would then be restarted from the point of turning on the air compressor.

Following the last test of the day, posttest end-to-end calibration of the instrumentation system was made. Fuel in the induction system was pushed back into the supply tank and the system thoroughly purged with nitrogen gas.

Immediately after each test, the data recorded on the FM tape recorder was played back onto a quick-look oscillograph at an expanded time scale of 8 to 1. This data told the test conductor that he did or did not get ignition, that the flame arrester quenched the flame, or that the flame penetrated through. If the flame arrester was penetrated and the flame speed was high, a playback record was made of the FM tape data at an expanded time scale of 32 to 1 for greater resolution. These records were then analyzed to determine flame speeds and peak pressure rise data.

SECTION VI

FACILITY CHECKOUT TESTS

A. SUBSCALE FLAME CHAMBER TESTS

A series of tests were made to check out facility systems installed specifically for the flashback flame tests. The initial tests were made in a subscale flame chamber while the full-scale chamber was being fabricated. These tests were conducted to evaluate the new hydrogen/air spark igniter system, the operating procedures required to fill an enlarged chamber with a combustible fuel/air mixture that could be verified with measurements on the total hydrocarbon analyser, the effectiveness of the frangible plastic chamber diaphragms, and, finally, the extent and nature of the problems associated with the flame plume emitted from both ends of the test chamber following the diaphragm rupture.

The subscale chamber shown in Figure 6-1 was made from an existing piece of steel pipe 0.91 m (3 ft.) in diameter and 2.13 m (7 ft.) long. It was mounted on supports at the exit end of the facility piping. A commercial Pres-Vac screen-flame arrester housing was installed downstream of the witness section for these check-out tests. Frangible diaphragms made from 6-mil-thick black polyethylene plastic sheeting covered both ends of the chamber. A nominal 15.2-cm- (6-in.-) diameter hole in the upstream diaphragm provided entrance for the fuel/air mixture, and a nominal 7.6-cm- (3-in.-) diameter hole in the downstream diaphragm provided the exhaust exit. The gas sampling probe for the hydrocarbon analyser was positioned at the center of the downstream hole. The hydrogen/air spark igniter was mounted on a length of pipe in the center of the chamber, such that the point of ignition was at the axial center line. A high-speed motion picture camera viewed the interior through a window port in the bottom of the flame chamber.

Seven test firings were made in the subscale flame chamber using gasoline/air mixtures at an injection equivalence ratio ranging from 1.1 to 1.3 (A/F = 13.29 to 11.24). The injection velocity was 1.52 m/s (5 ft/s) through the 15.2-cm- (6-in.-) diameter piping. Three tests were made with a dual 20-mesh screen arrester installed in the Pres-Vac housing, and four were made with the arrester screens removed. Energetic flames were recorded in the chamber when ignition was made after the hydrocarbon analyser measured an equivalence ratio of 0.7 (A/F = 20.88) or higher in the exhaust flow. The flames entered the piping on every test where the screen arrester was removed. On the first two tests with the screen arrester installed, the flames were quenched. However, on the last test the flame did penetrate the dual 20-mesh screen arrester and enter the facility piping. The motion picture data from this test showed that the hydrogen/air spark igniter was still burning at the time the propagating flame entered the arrester housing. This would have resulted in excessive flame speed that caused the arrester failure. Posttest inspection revealed no damage to the screen arrester.

Both chamber diaphragms ruptured and burned on all tests. The peak chamber pressure rise recorded ranged from 2.07 to 2.76 kN/m^2 (0.3 to 0.4 psid). The visible flame plume emitted from both ends of the chamber extended for a distance of about 1 m (3.3 ft.). All instrumentation and cabling within this area required flame protective covering. The audible noise associated with diaphragm rupture was minimal. Flashback flame in the facility piping did not produce detonations.

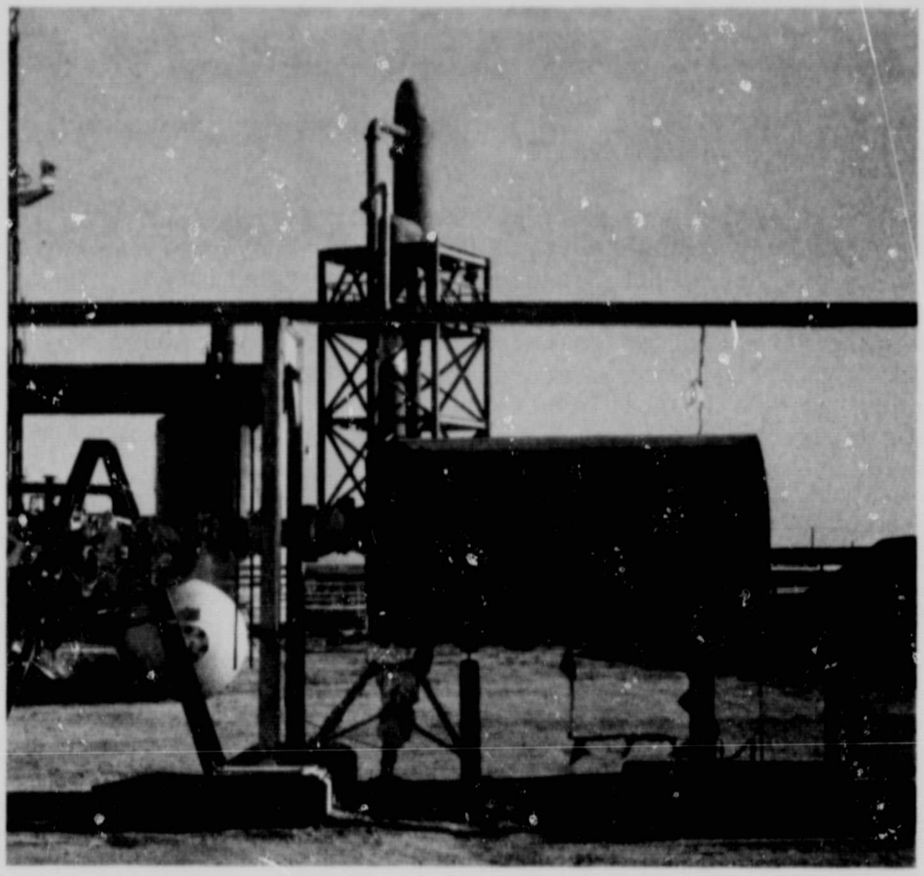


Figure 6-1. Subscale Flame Test Chamber Installation on B-Stand

B. FULL-SCALE FLAME CHAMBER TESTS

The full-scale flame chamber is described in Subsection III-G and shown in Figure 3-5. Test fuel was changed from gasoline to commercial-grade propane for these check-out tests. The injection equivalence ratio for propane/air mixture was 1.1 (A/F = 14.26) at a flow velocity of 1.52 m/s (5 ft/s). A total of twenty-one flashback flame test firings were made with eleven different test configurations (see Appendix A, Test Configuration Log). The first thirteen test firings were made with the Pres-Vac dual 20-mesh screen arrester installed. Ignition and combustion were obtained with propane/air mixtures when the hydrocarbon analyser indicated an equivalence ratio of 0.8 (A/F = 19.60) or higher. With the igniter in the downstream position, the propagating flame was quenched at the test arrester. The flame sensors located adjacent to the igniter position recorded the initial flame front, but their signals were driven off-scale by ambient light entering the chamber through the ruptured diaphragms. The flame speeds could not be calculated because of the lost signals.

The igniter was relocated to the center of the chamber and the test firings were repeated. With this configuration, the flame sensors recorded flame propagation in both the upstream and downstream directions before the chamber diaphragms were blown out. Calculated flame speeds ranged from 1.5 to 4.6 m/s (5 to 15 ft/s) and the flame did not penetrate the screen arrester. All chamber pressure sensors simultaneously recorded a peak pressure rise around 1000 N/m^2 (0.145 psid) just before the diaphragms ruptured.

The igniter was relocated to the upstream position, which placed the point source of ignition only 76.2 cm (30 in.) from the downstream face of the screen. One test firing was made with this configuration where the flame penetrated through the screen arrester and into the facility piping. Posttest inspection did not reveal any damage to the screens. Motion pictures taken of this test showed the ignition sequence and the rapidly expanding spherical flame front. It was estimated that the flame speed was in excess of 15.2 m/s (50 ft/s). This unusually high flame speed was most likely caused by the localized influence of the hydrogen/air spark igniter that was programmed for 2.0 seconds duration. The igniter duration was reprogrammed to only 0.2 seconds (200 ms) on all subsequent tests; this eliminated the high initiation flame speed.

When the igniter was relocated to the downstream position, a 1.52-m- (5-ft.-) diameter aluminum plate was installed to cover the central area of the plastic diaphragm on the flame chamber exit. This flame shield covered about 40% of the total exposed area and delayed the rupture of the diaphragm for a sufficient length of time to allow the flame to traverse the length of the chamber. Motion pictures taken of test firings after this modification showed that the flame propagation path was predominantly in the lower half of the chamber. It is believed that this is caused by gravitational stratification of the fuel/air mixture as it enters the chamber. The 1.52-m/s (5-ft/s) injection velocity is not sufficient to produce turbulent mixing within the large chamber volume. It is, however, representative of the worst-case condition of a fuel storage tank venting vapors on a calm day. The results would be a flammable concentration of fuel vapors collecting in the tank area, causing a very hazardous condition. In the test chamber, the stratified flame produced very inconsistent readings on the flame sensors mounted along the horizontal center line. To correct this situation, the flame sensors were relocated along the top center line, where the field of view looking down into the chamber included the low level flames. The resulting flame speed measurements were much more consistent.

The flame screen assembly, which is mounted in the center of the Pres-Vac housing, was 20.3 cm (8 in.) upstream of the exit flange. In this position, the screen surface was not visible to the motion picture camera and the flashback flame impingement on the surface of the screen could not be photographed. For the last series of checkout tests, the Pres-Vac housing was replaced with a short 15.2-cm- (6-in.-) diameter flanged pipe spool section to provide the adaptor mounting for the screen flame arresters. The screens were installed between two flanges at the pipe spool exit, where they would be in full view of the motion picture camera. Figure 6-2 is a photograph of a single 30-mesh screen arrester mounted in the pipe spool adapter. Two test firings were made with this test assembly using propane and air mixture at an equivalence ratio of 1.1 and a flow velocity of 1.52 m/s (5 ft/s). Both the upstream and downstream igniter positions were used. Flame speeds from 4.5 to 7.62 m/s (15 to 25 ft/s) were recorded and the flame did not penetrate the single 30-mesh screen arrester on either test.

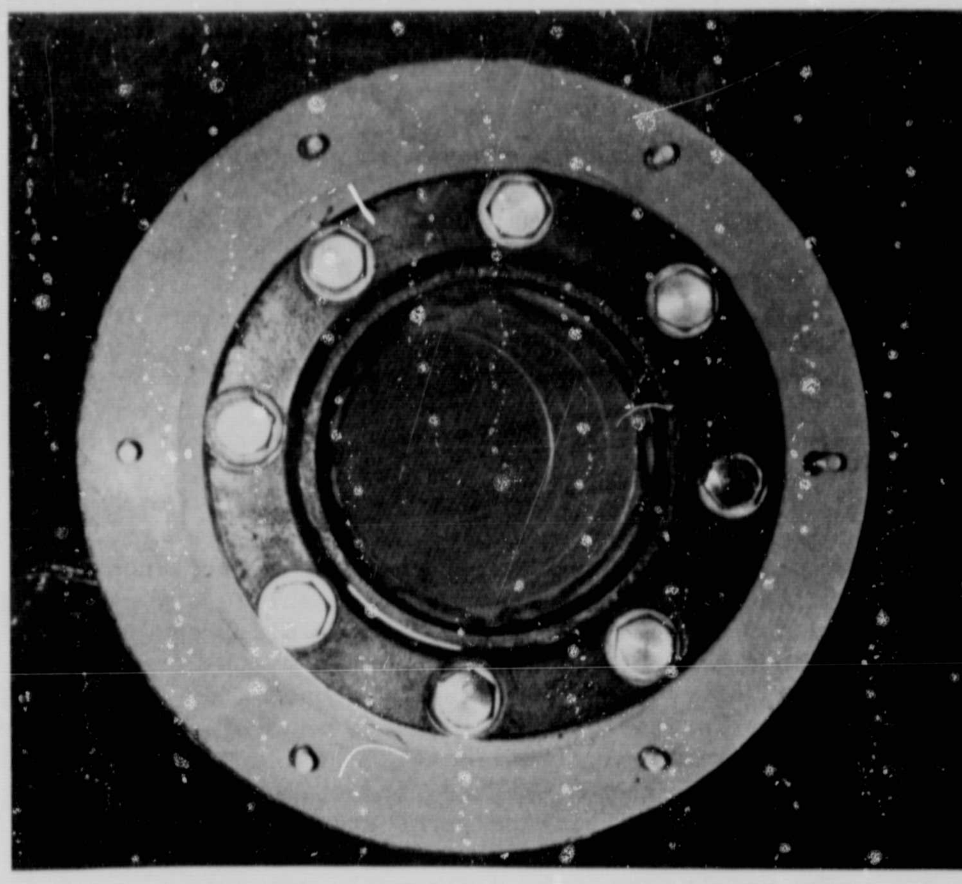


Figure 6-2. Single 30-Mesh Screen Arrester Mounted in Pipe Spool Adapter

The motion pictures showed the propagating flame impinging on the surface of the screen where it continued to burn for time periods up to 25 seconds without causing any damage, other than discoloration, to the screen.

The final series of tests for the facility checkout were made without any arrester installed in the pipe spool adaptor (Test Configuration No. 112). Four firings were made with the propane/air mixture at an equivalence ratio of 1.1 and a flow velocity of 1.52 m/s (5 ft/s). Both upstream and downstream igniter positions were used. The flame penetrated into the facility piping on each firing and propagated up to the inlet crimped ribbon arrester, but not beyond. No detonations were developed in the piping. On some tests, the back-pressure pulse was strong enough to rupture one or more of the low-pressure burst discs in the induction system piping. However, posttest inspections revealed no damage.

At the completion of this last series of checkout tests, the flashback flame chamber test facility was determined to be operational. The test program was

started to evaluate the four selected types of flame arresters with one or more of the eight preselected fuels. To reduce the number of possible tests, a standard test condition was established that would use an injection equivalence ratio (1.0 to 1.2) producing the theoretical maximum flame speed for the particular fuel/air mixture in use and an inlet piping flow velocity of 1.52 m/s (5 ft/s). Ignition would be initiated at an equivalence ratio (0.7 to 0.9) well above the lower flammability limit as measured by the total hydrocarbon analyser sampling the mixture flowing in the exhaust-burn stack.

SECTION VII

DESCRIPTION OF FLAME ARRESTER TEST ASSEMBLIES

A. GENERAL

The U.S. Coast Guard has approved the use of both a single 30-mesh screen and the dual 20-mesh screen configuration for screen flame arresters on U.S. flag vessels. Their purpose is the prevention of flame passage from the open deck into cargo tanks through vent outlets, ullage ports, hatches, or butterworth plates. The wire cloth material used for these screens must be resistant to the marine environment, i.e., resistant to chemical corrosion and salt water rusting. In addition, the wire material must be resistant to high-temperature oxidation in the event an accidental flame impinges on the screen surface for a prolonged period of time.

These requirements served as guidelines for the selection of flame screen arresters to be experimentally evaluated as part of the U.S. Coast Guard funded portion of this program. The NASA funded portion was directed at evaluating two generically different types of flame arresters, namely the spiral-wound, crimped metal ribbon, and the packed bed of Ballast rings. These two types of flame arresters have been shown to be very effective in quenching gasoline/air mixture detonations in a piping system, as reported in Reference 2-10. The propagating flame speeds for detonations were in excess of 1800 m/s (5906 ft/s). It remained to be demonstrated that these arresters are also effective against flames with speeds in the range of 1.5 to 9.1 m/s (5 to 30 ft/s), and that they remain effective under sustained burning test conditions for periods up to 30 minutes.

B. SINGLE 30-MESH SCREEN ARRESTER

The single 30-mesh screen arrester was made from standard-grade stainless-steel type 316 wire cloth having the following dimensions:

Mesh size:	30 × 30 per lineal inch
Wire diameter:	0.033 cm (0.013 in.)
Hydraulic radius:	0.0516 cm (0.0203 in.)
Open area:	37.1%

The type 316 stainless-steel wire is highly resistant to chemical corrosion and rusting. It will also resist thermal oxidation at temperatures up to 760°C (1400°F). Nichrome wire has a higher thermal oxidation resistance, up to 972°C (1700°F), but is less readily available in wire cloth weaves.

The single screen, with a Vellumoid gasket on either side, was installed between the exit flange of the 15.2-cm- (6-in.-) diameter pipe spool adapter and a bolted-up, slip-on flange used for clamping, as shown in Figure 6-2. The fuel/air mixture flow velocity in the facility piping varies inversely with the cross-sectional flow area, therefore the standard 1.52-m/s (5-ft/s) flow velocity increases to 4.1 m/s (13.5 ft/s) in passing through the 30-mesh screen attached at the end of the pipe.

C. DUAL 20-MESH SCREEN ARRESTER

The dual 20-mesh screen arrester was made from standard grade stainless-steel type 316 wire cloth having the following dimensions:

Mesh size:	20 × 20 per lineal inch
Wire diameter:	0.041 cm (0.016 in.)
Hydraulic radius:	0.086 cm (0.034 in.)
Open area:	46.2%

The two screens were installed on the pipe spool adapter using the same method as the single screen, but with the addition of a 2.54-cm- (1.0-in.-) thick spacer separating the two screens. An exploded view of the components in this assembly is shown in Figure 7-1, and the test installation is shown in Figure 7-2. The fuel/air mixture flowing at standard conditions in the facility piping accelerated to 3.3 m/s (10.7 ft/s) during passage through the 15.2-cm- (6-in.-) diameter 20-mesh screens.

D. SPIRAL-WOUND, CRIMPED METAL RIBBON ARRESTER

The spiral-wound, crimped metal ribbon arrester was the optimum configuration developed as the results of the parametric phase of the testing reported in Reference 2-10. It was made from a commercially available Shand and Jurs spiral-wound, crimped stainless-steel core element having the following dimensions:

Diameter:	30.5 cm (12 in.)
Length (L):	20.3 cm (8 in.)
Ribbon thickness:	0.0089 cm (0.0035 in.)
Crimp height:	0.160 cm (0.063 in.)
Crimp width:	0.350 cm (0.138 in.)

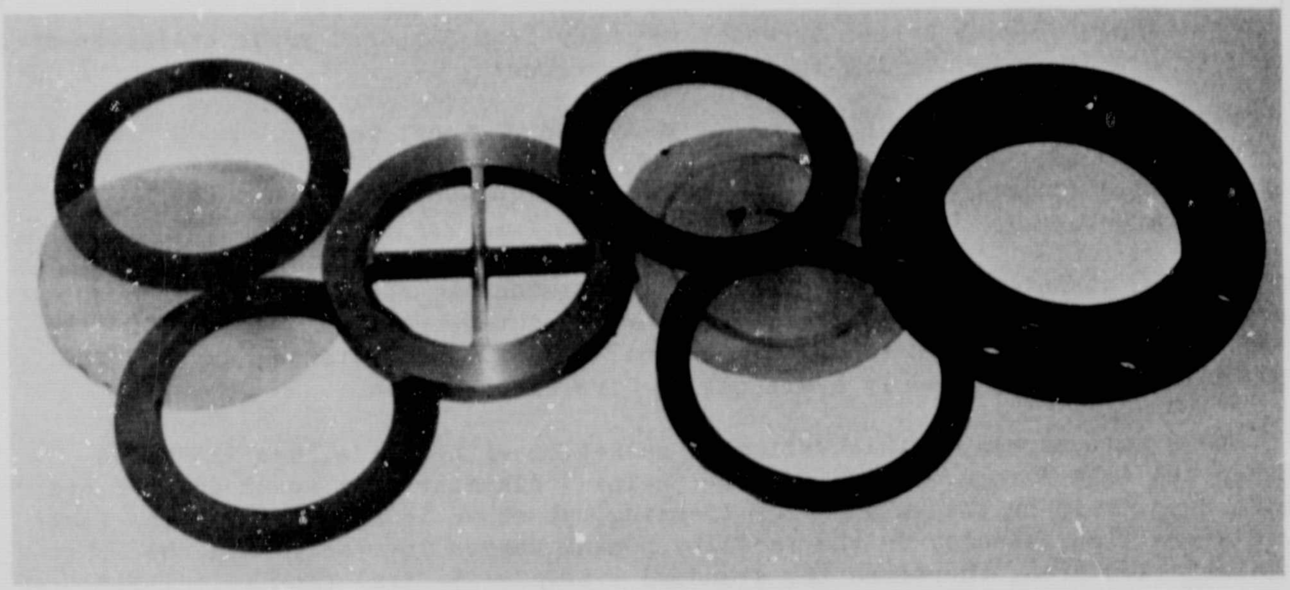


Figure 7-1. Exploded View of Components for a Dual 20-Mesh Screen Arrester

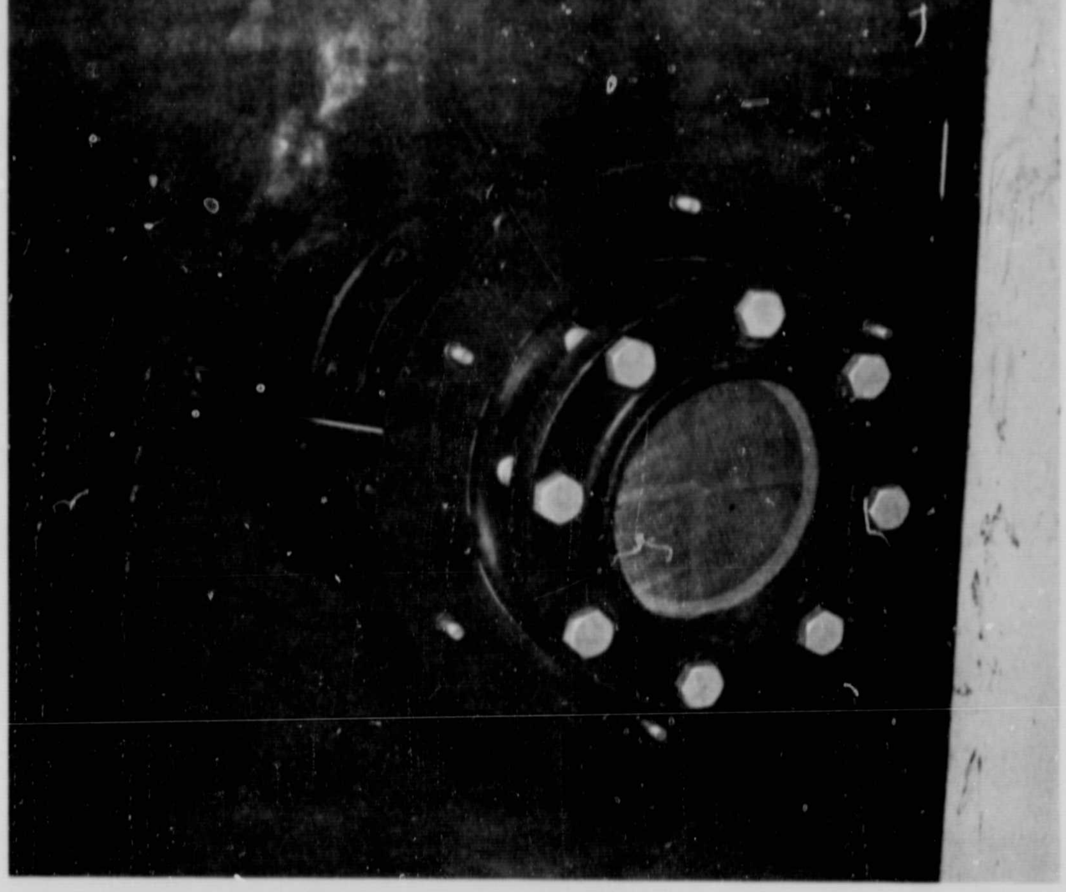
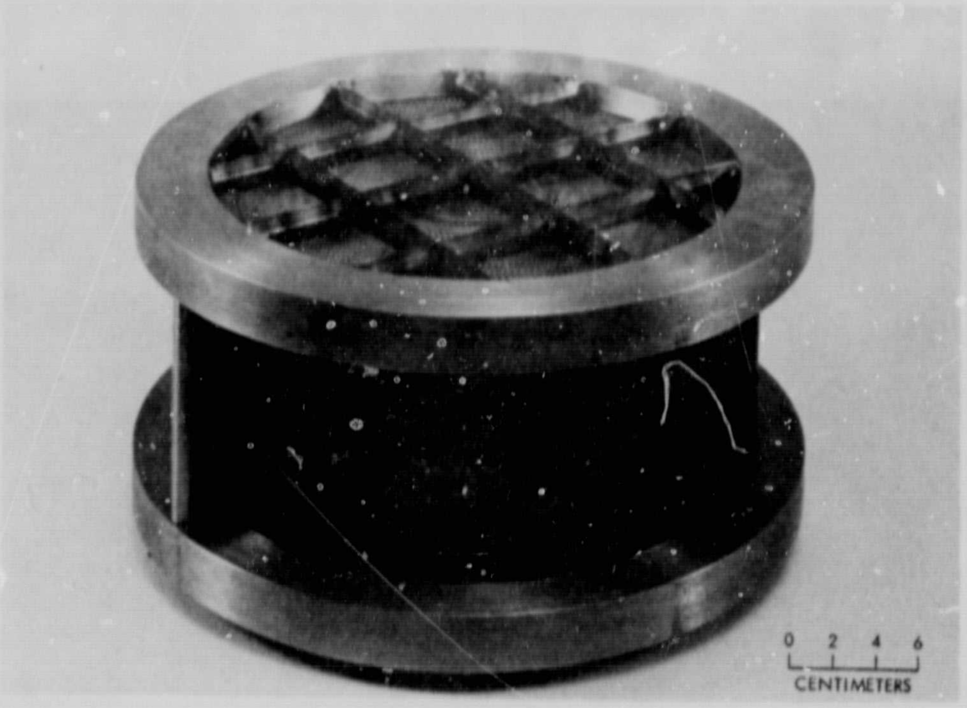


Figure 7-2. Dual 20-Mesh Screen Arrester Test Installation

Hydraulic diameter (D_h):	0.0376 cm (0.54 in.)
Length to diameter ratio (L/D_h):	148
Open area:	87.6%

The crimped ribbon core element was pressed into a housing made from a short length of extra-strong 30.5-cm- (12-in.-) diameter steel pipe and held in place by mounting rings with retainer grids attached to each end, as shown in Figure 7-3. A flanged concentric pipe reducer, 30.5-cm to 15.2-cm (12-in. to 6-in.) diameter was used as an adaptor mounting to install the crimped ribbon arrester assembly on the exit of the facility piping, as shown in Figure 7-4. The fuel/air mixture flow velocity at the standard test condition through this arrester was 0.5 m/s (1.6 ft/s).



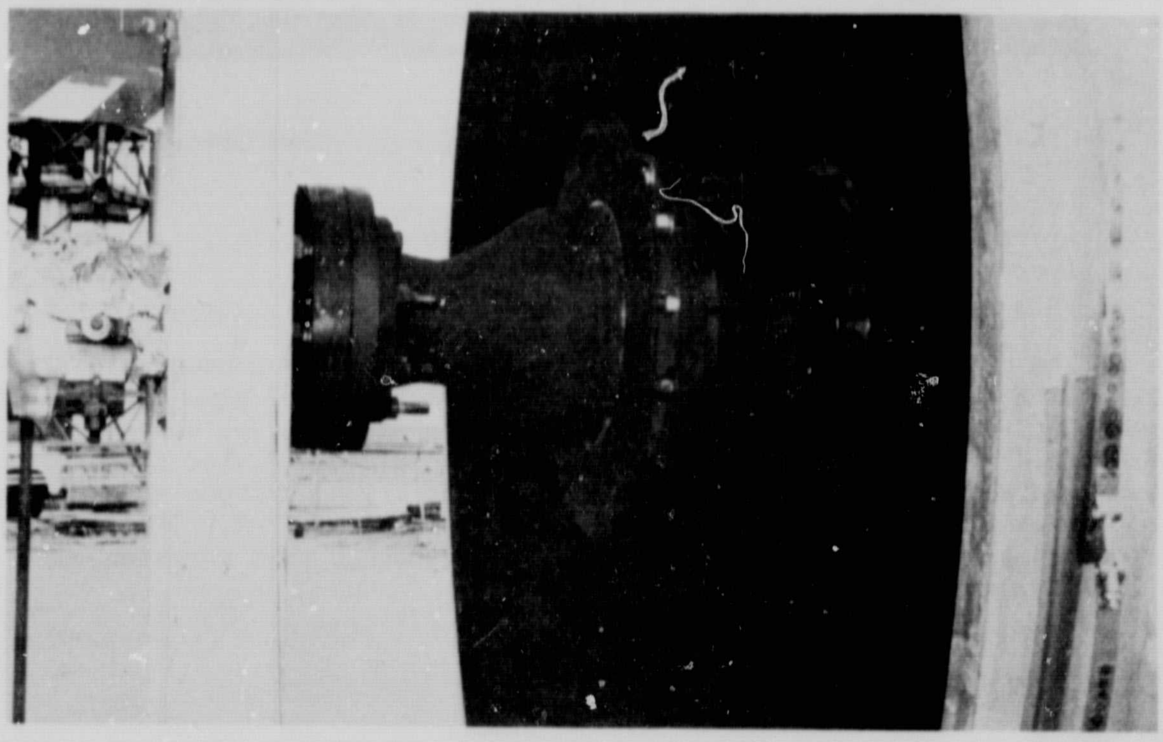


Figure 7-4. Crimped Ribbon Arrester Test Installation

E. PACKED BED OF BALLAST RINGS ARRESTER

The configuration for the packed bed of Ballast rings arrester was also developed during the parametric phase of testing reported in Reference 2-10. It has the following optimized dimensions:

Bed diameter:	25.4 cm (10 in.)
Bed length:	45.7 cm (18 in.)
Bed volume:	3605 cc (1419 cu. in.)
Packing material:	aluminum Ballast rings
Ring size:	2.54 cm (1.0 in.) in diameter × 2.54 cm (1.0 in.) long
Open area:	60% (estimated)

The rings were randomly packed in 25.4-cm- (10-in.-) diameter flanged pipe housing and held in place with an expanded metal grid, as shown in Figure 7-5. A flanged concentric pipe reducer, 25.4-cm to 15.2-cm (10-in. to 6-in.) diameter, adapted the inlet end of the arrester housing for installation on the exit of the facility piping as shown in Figure 7-6. The estimated fuel/air mixture flow velocity through this arrester at the standard test condition was around 0.9 m/s (3.0 ft/s).

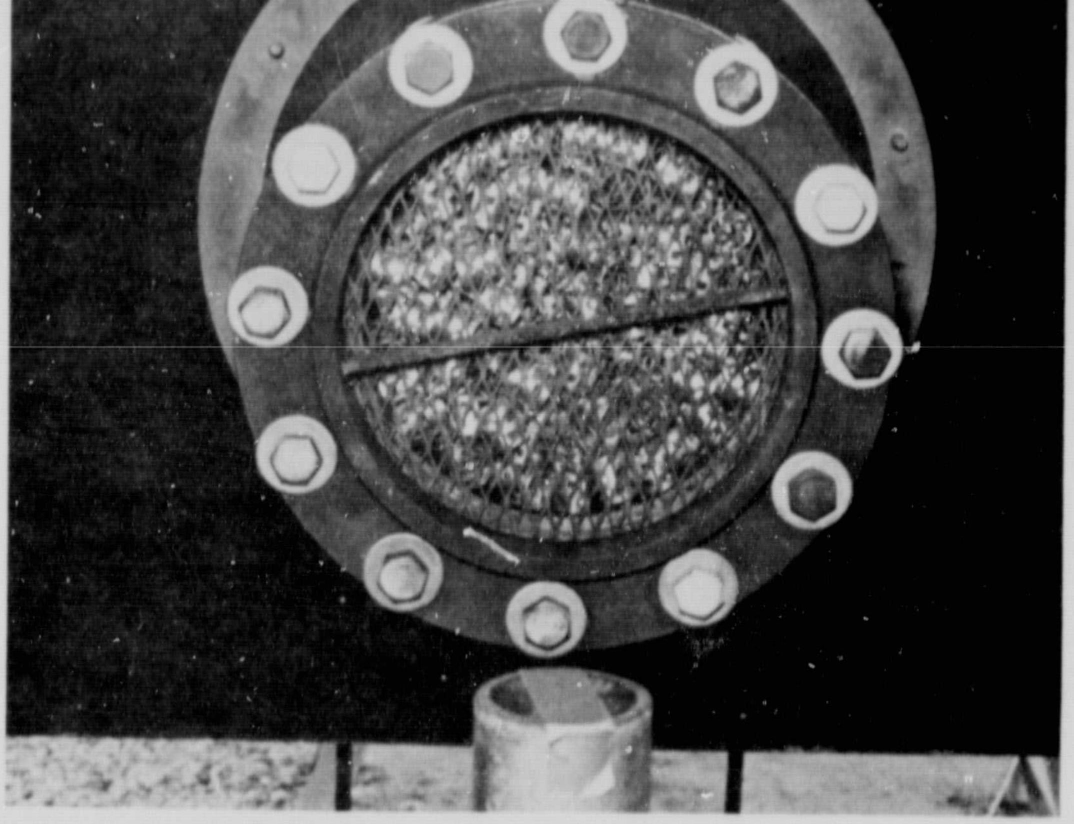


Figure 7-5. Packed Bed of Aluminum Ballast Rings Arrester Assembly

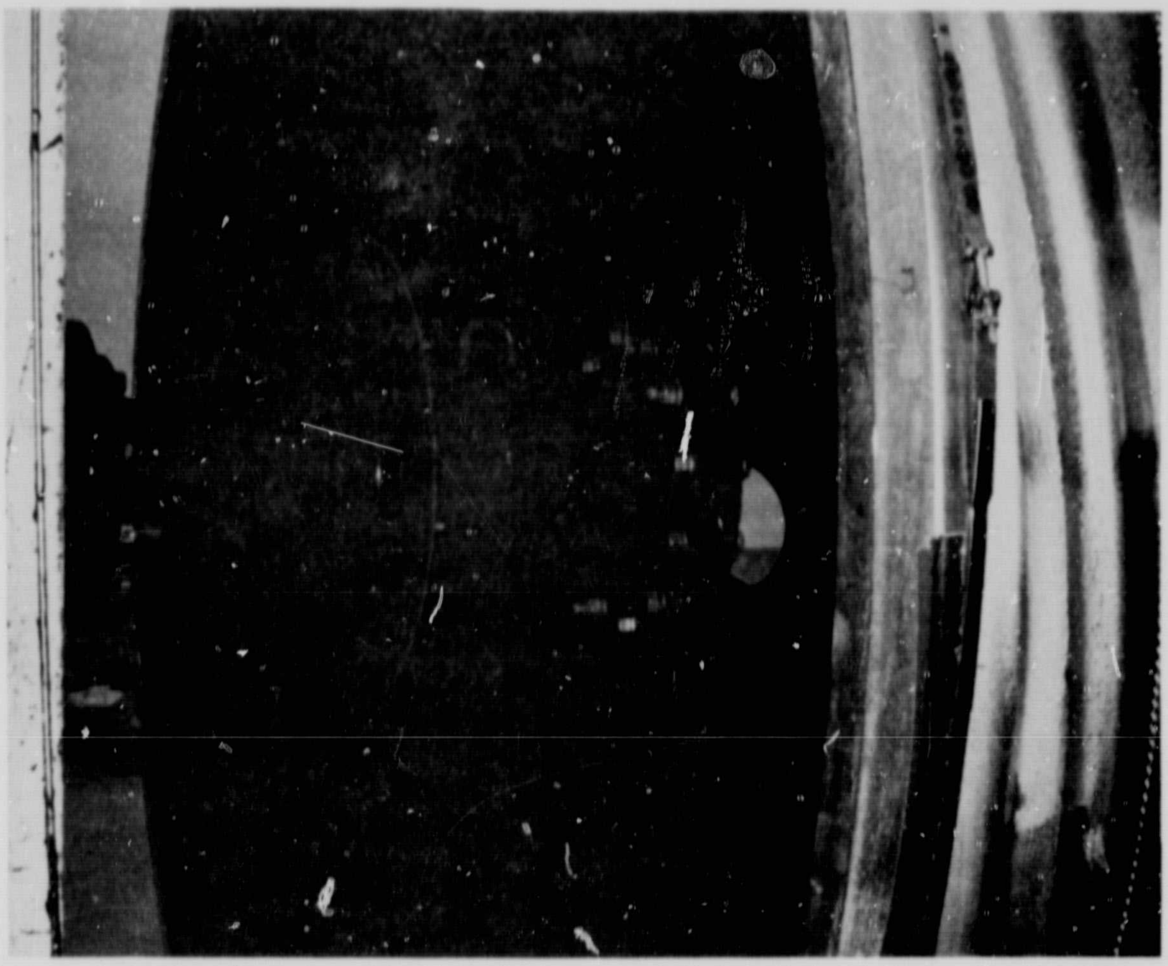


Figure 7-6. Packed Bed of Rings Arrester Test Installation

SECTION VIII

FLASHBACK FLAME ARRESTER TESTS

A. TEST PROGRAM LOGIC

The test program for screen flame arresters followed the logic diagram presented in Figure 8-1. After the selection of the flame arrester test configurations, the first screening test series was performed in the flashback flame chamber to evaluate both the single 30-mesh and the dual 20-mesh screen arresters with a propane/air mixture. Propane was selected as the first test fuel because it had one of the lowest probable flame speeds of the representative bulk cargo fuels. The upstream igniter position was used first; it was thought to produce the less severe flame speed condition because of the shorter run-up distances for flame propagation. This was followed by tests using the downstream igniter position, assuming that it was more severe. A minimum of three test firings were made for each test configuration to determine the success or failure of the arrester. If a screen flame arrester failed to quench the flashback flame on any of these initial tests, it was to be deleted from the program.

The second screening test series was performed to evaluate the successful flame arrester configuration(s) from the first series, using an ethylene/air mixture because it had the highest probable flame speed of the representative bulk cargo fuels. Both the upstream and downstream igniter positions were used. Upon completion of the ethylene/air mixture tests, one or both of the screen flame arresters was to be selected for additional testing with the six alternate types of fuel/air mixtures. The selection of arrester configurations was made by the U.S. Coast Guard, based upon the test results and the recommendations provided by JPL.

Additional evaluation test series were made in the flame chamber with the selected arrester configurations using the following representative bulk cargo fuels: (1) acetaldehyde, (2) butane, (3) ethyl ether, (4) gasoline, (5) methyl alcohol, and (6) toluene. The igniter position was selected to produce the most severe flashback flame propagation condition as determined from the measured flame speed advancing toward the face of the test arrester in the first two screening test series.

A final evaluation test series was made using the successful arrester configurations from the previous testing to evaluate their heat-up and quenching capabilities in the sustained flame facility. The flame from a propane/air mixture at the standard test condition was stablized on the downstream face of the arrester for a period of 30 minutes. These tests were used to determine if the arrester can continue to function after reaching an elevated steady-state, soak-back temperature without structural damage. A single test for the full duration of 30 minutes, without a flame penetration, was sufficient to demonstrate the successful performance of any arrester configuration. If a flame did penetrate the test arrester, the test would be repeated to verify the failure.

The two NASA-funded flame arrester configurations, the spiral-wound, crimped metal ribbon and the packed bed of aluminum Ballast rings, were inserted into the program following the second screening test series. They were evaluated in the

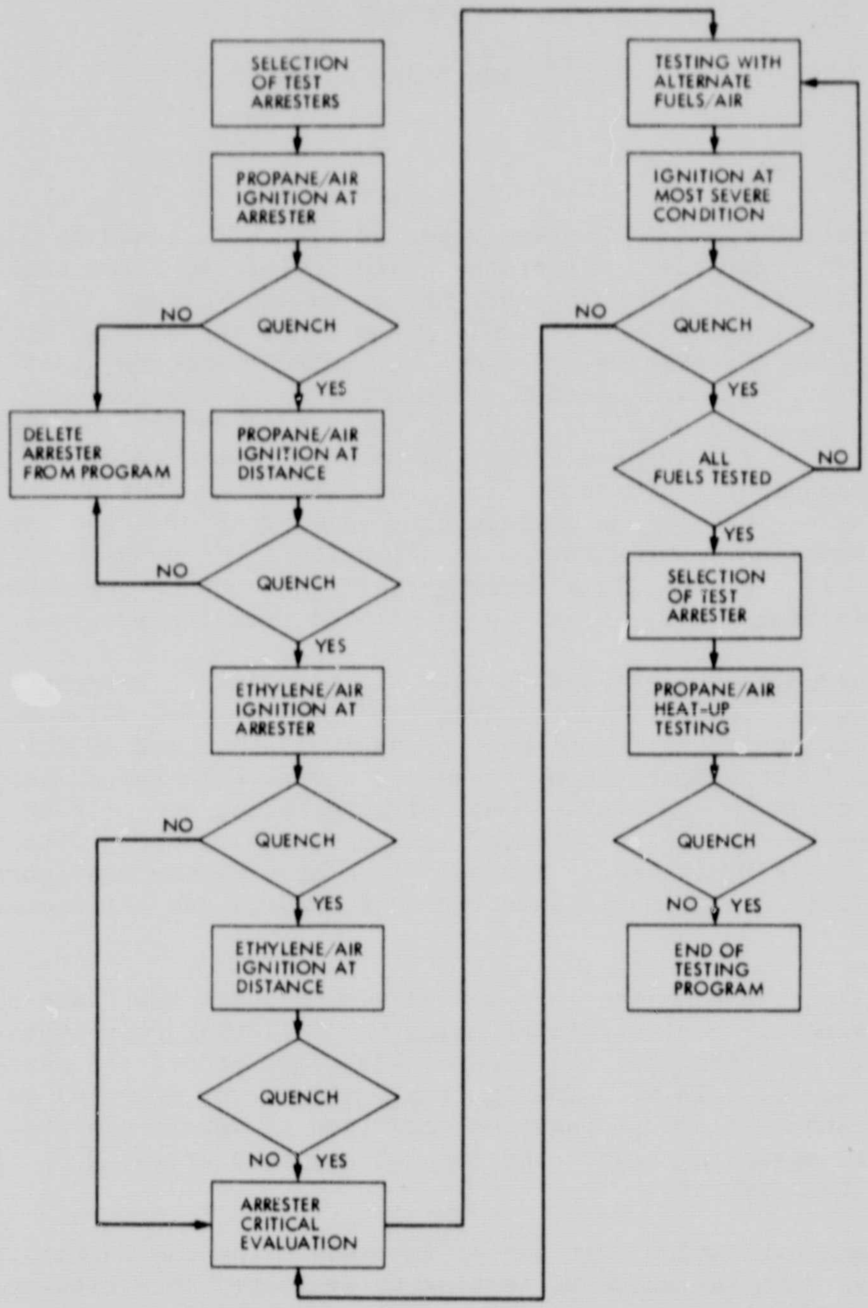


Figure 8-1. Screen-Type Flashback Flame Arrester Test Program Logic Diagram

flashback flame chamber with three fuels: (1) propane, (2) ethylene, and (3) gasoline. The igniter position was selected for the most severe test condition. They were also evaluated in the sustained burning facility using both propane/air mixture and ethylene/air mixture at the standard test condition.

B. PROPANE/AIR MIXTURE SCREENING TESTS

The first series of screening tests were made with propane/air mixture at the standard test condition where the injection equivalence ratio was 1.14 (A/F = 13.75). Fill time required to obtain a good combustible mixture in the flame chamber was 600 seconds. The nominal equivalence ratio at ignition was 0.87 (A/F = 18.02) as measured by the total hydrocarbon analyser sampling the fuel/air mixture in the exhaust-burn stack. Tests were made with the dual 20-mesh screen arrester and the single 30-mesh screen arrester using both the upstream and downstream igniter positions (Test Configuration Nos. 113 to 116). Successful ignition and combustion was achieved on all test firings. The flashback flames did not penetrate either of these screen-type arresters on any test.

The upstream igniter position produced an average flame speed between the point source of ignition and the arrester (F81-F82, Table 4-1) that measured 4.8 m/s (15.7 ft/s). The flame speed moving in the direction of flow (downstream) increased to an average of 13.6 m/s (44.6 ft/s) before it exited the downstream end of the flame chamber (F86-F87). Average peak pressure rise in the chamber (DP81 to DP87) ranged from 1139 to 974 N/m^2 (0.165 to 0.141 psid). A plot of the results from these tests is shown in Figure 8-2. Also shown on this plot are the flame speeds in the facility piping that occurred on the last checkout test, when an arrester was not installed. The flame entered the piping (F81-F73) at 2.3 m/s (7.5 ft/s) and accelerated up to 18.9 m/s (62.0 ft/s) at the facility inlet arrester (F21-F12). A tabular summary of averaged flame speed data and peak pressure rise data is presented in Table 1-1. A tabular summary of all steady-state data is presented in Appendix B and a tabular summary of all transient-state data is presented in Appendices C and D.

The average flame speeds recorded in this test chamber when using the downstream igniter position (Test Configuration Nos. 114 and 115) were more uniform and lower in value, as shown in the data plot, Figure 8-3. A maximum flame speed of 4.2 m/s (13.8 ft/s) occurred just upstream of the igniter (F86-F87). The flashback flame speed propagating against the direction of flow (upstream) was only 3.0 m/s (9.8 ft/s). This is about one half the speed obtained using the upstream igniter position. Peak pressure rise data were also more uniform and slightly lower, with an averaged value of 810 N/m^2 (0.117 psid).

The results of these first screening tests indicate that both the dual 20-mesh screen arrester and the single 30-mesh screen arrester are effective in quenching flashback flames with a nominal flame speed up to 6.3 m/s (20.7 ft/s). The more severe test condition in the flame chamber is produced when the igniter is located in the upstream position. The flame speed data obtained from the motion picture films corroborate these test results. It was apparent in the films that the degree of intensity (brightness) in the propagating flame front correlated to the regions of optimum fuel/air mixture ratio and higher levels of localized turbulence. When the upstream igniter position was used, a bright band

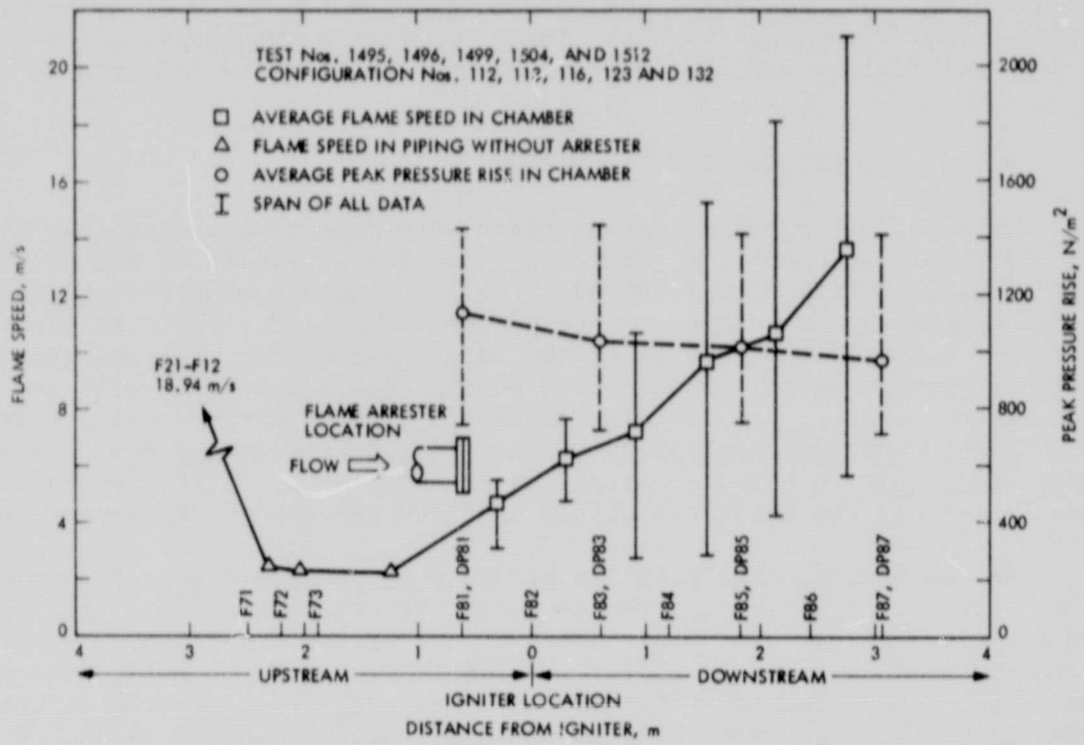


Figure 8-2. Propane/Air Mixture Using Upstream Igniter Position Test Results

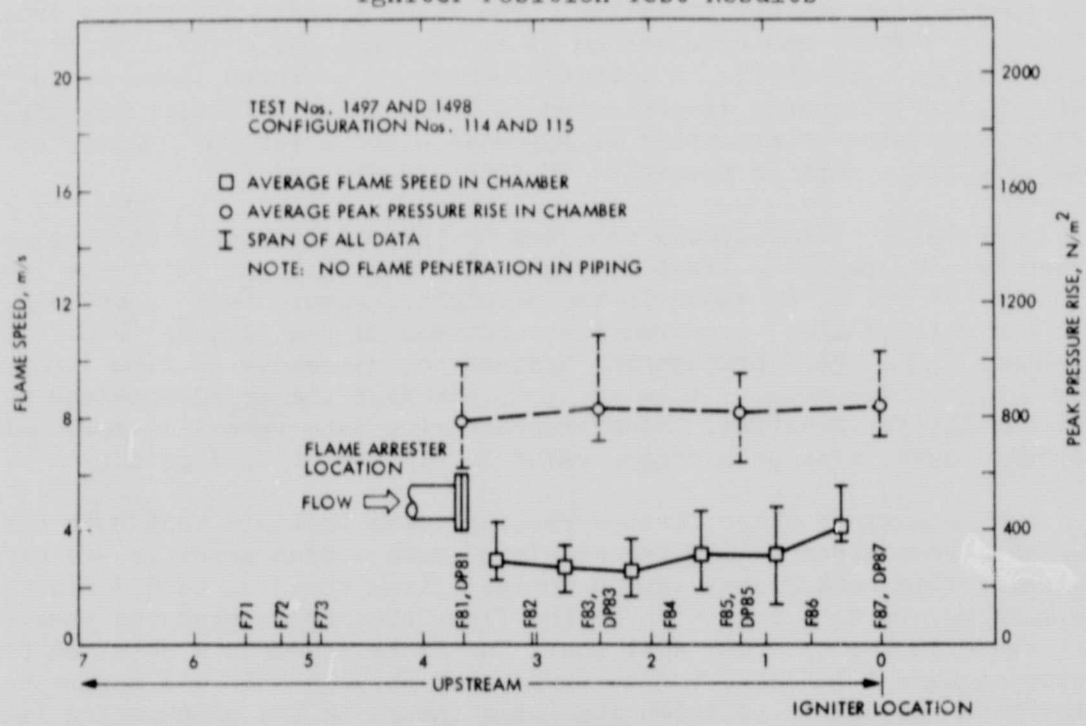


Figure 8-3. Propane/Air Mixture Using Downstream Igniter Position Test Results

of flame could be seen accelerating upstream through the center core flow of the plume of the fuel/air mixture as it expanded from the facility piping. The fuel/air mixture ratio in the expanding plume became stratified by gravitational effects: the heavier hydrocarbon vapors settled to the bottom of the test chamber. When the downstream igniter position was used, the propagating flame could be seen in the films concentrated mainly in the lower half of the chamber with a very broad and diffused flame front moving relatively slowly upstream. This flame front increased in brightness and accelerated in speed as it progressed up the plume to the test arrester installed on the facility piping.

C. ETHYLENE/AIR MIXTURE SCREENING TESTS

The second series of screening tests were made with an ethylene/air mixture at the standard test conditions. The injection equivalence ratio was 1.15 (A/F = 12.86) for maximum flame speed. Fill time required to charge the flame chamber with a combustible mixture of this gaseous fuel was reduced to 400 seconds. The nominal equivalence at the time of ignition was 0.70 (A/F = 21.1). Both the dual 20-mesh screen arrester and the single 30-mesh arrester were used in these tests with upstream and downstream igniter positions (Test Configuration Nos. 117 to 122).

A problem started on the first test when it was discovered that a sustained flame developed inside the exhaust burn stack piping during the chamber filling operations. It is believed the flame originated from the natural gas fired burner at the top of the stack. Once the ethylene/air exhaust reached a flammable mixture level, a flashback flame from the burner impinged on the exit arrester. The relatively high flame speed of the ethylene/air mixture and the low flow velocity at this location allowed the flame to penetrate into the core of the arrester. It heated the stainless-steel crimped ribbon up to the spontaneous ignition temperature (490°C) for ethylene fuel. At this point, the flame passed through the exit arrester, propagated up the piping, and held on the downstream face of the inlet arrester. Other than blistering the paint on the outside of the piping, this caused no structural damage.

In the inlet arrester of the exhaust-burn stack had a core element made of spiral-wound, crimped aluminum ribbon. It was four times as long as the exit arrester, 15.2 cm (6 in.) compared to 3.8 cm (1.5 in.), and approximately the same diameter. This larger mass of metal, having higher heat capacity, apparently prevented the lean ethylene/air flame from penetrating through the inlet arrester. Consequently, the exit arrester was replaced with a unit similar to the inlet arrester. The results indicated no further incidents of sustained flames in the exhaust-stack piping and the test program to evaluate screen-type arresters using ethylene/air mixture flames continued.

The average flame speeds recorded in the flame chamber when using the downstream igniter position (Test Configurations No. 119 and 121) ranged from 7.8 m/s (25.6 ft/s) at the igniter (F86-F87) to 4.4 m/s (14.4 ft/s) at the arrester (F81-F82). The average peak pressure rise in the chamber was 931 N/m^2 (0.135 psid). A plot of the test results are shown in Figure 8-4. Both types of screen flame arresters were successful in quenching these ethylene/air mixture flashback flames.

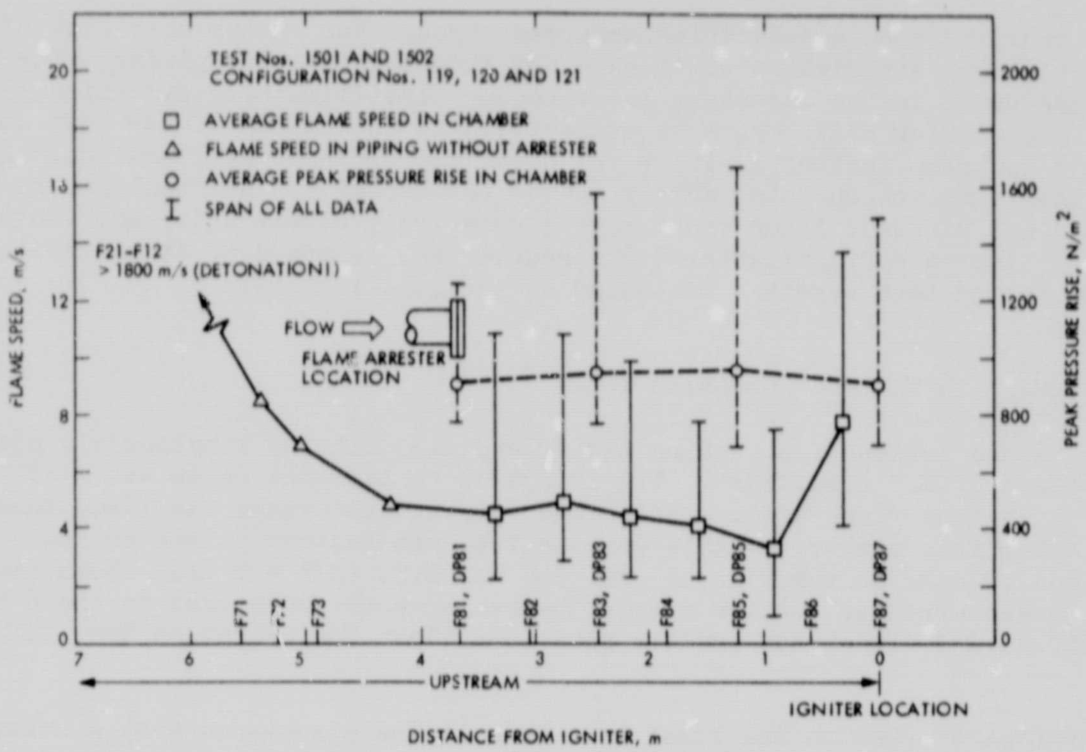


Figure 8-4. Ethylene/Air Mixture Using Downstream Igniter Position Test Results

When the arrester was removed from the end of the facility pipe, the flame entered the pipe (F81-F73) at a speed of 4.9 m/s (16.1 ft/s) and accelerated to a detonation at the inlet arrester (F21-F12) with speeds in excess of 1800 m/s (5905 ft/s). The detonation did not produce any damage to the test facility systems.

The average flame speeds recorded in the flame chamber when using the upstream igniter position (Test Configuration Nos. 117, 118, and 122) ranged from 6.6 m/s (21.6 ft/s) at the arrester (F81-F82) to 16.3 m/s (53.5 ft/s) at the downstream chamber exit (F86-F87). The average peak pressure rise in the chamber was 1102 N/m^2 (0.160 psid). A plot of the test results are shown in Figure 8-5. The single 30-mesh screen arrester was successful in quenching all flashback flames, whereas the dual 20-mesh screen arrester failed to quench any of the flashback flames in three test firings. The flame that penetrated through the arrester screen housing decelerated briefly to 3.9 m/s (12.8 ft/s) in the facility piping (F81-F73), and then quickly accelerated to a detonation before reaching the facility inlet arrester (F21-F12). Posttest inspection of the screens following each flame penetration did not reveal any damage to the screen wire that could have caused this failure.

The results of the second screening tests indicate that the single 30-mesh screen arrester is effective in quenching flashback flames with nominal flame speeds up to 6.6 m/s (21.6 ft/s). The dual 20-mesh screen arrester is not effective at this higher flame speed, and the limiting flame speed will have to

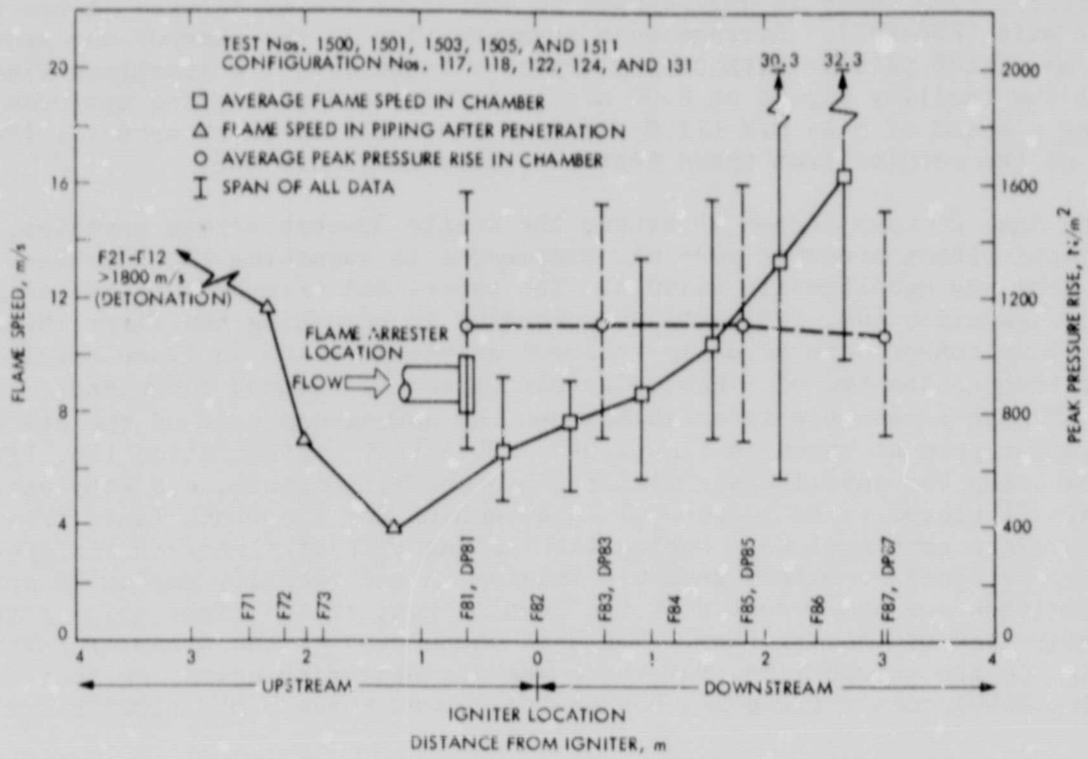


Figure 8-5. Ethylene/Air Mixture Using Upstream Igniter Position Test Results

be determined from additional tests. The upstream igniter position again resulted in the more severe test conditions when using ethylene/air mixture in the flame test chamber. Photographic data of flame speeds taken from the motion picture films corroborated these test results. In accordance with the logic diagram, Figure 8-1, the follow-on alternate fuels tests were limited to using the upstream igniter position only.

D. GASOLINE/AIR MIXTURE TESTS

The first series of alternate fuels tests were made with a gasoline/air mixture at the standard test condition. The injection equivalence ratio was 1.10 (A/F = 17.29) for maximum flame speed. Time required to fill the test chamber varied depending on the ambient temperature, but averaged around 900 seconds. The nominal equivalence ratio for ignition was 0.70 (A/F = 20.89). Tests were made using the dual 20-mesh screen arrester, the single 30-mesh screen arrester, the spiral-wound, crimped stainless-steel ribbon arrester, and the packed bed of aluminum Ballast rings arrester (Test Configuration Nos. 125 to 130). All tests were made with the igniter in the upstream position.

The average flame speed between the igniter and the downstream face of the test arresters (F81-F82) was 4.22 m/s (13.3 ft/s). The highest average flame speed was measured just downstream of the igniter (F82-F83) at 6.01 m/s

(19.7 ft/s); from there it decelerated to only 2.92 m/s (9.6 ft/s) at the flame chamber exit (F86-F87). Average peak pressure rise in the chamber was around 1018 N/m^2 (0.148 psid). Without any arrester installed, the flashback flame entered the facility piping at 2.00 m/s (6.6 ft/s) and propagated upstream reaching a speed of 5.44 m/s (17.8 ft/s) at the facility inlet arrester (F21-F12). A plot of the results from these tests is shown in Figure 8-6.

The dual 20-mesh screen arrester, the single 30-mesh screen arrester, and the crimped ribbon arrester were all successful in quenching the flashback flames from the gasoline/air mixture. The packed bed arrester, in the original test configuration (No. 129), was unsuccessful in quenching the first three firings. Flame sensor data actually recorded an acceleration in flame speed during passage through the bed of rings, possibly caused by induced turbulence. A single 30-mesh screen was inserted between the downstream face of the bed and the retainer grid as shown in Figure 8-7. This test configuration (No. 130) was retested using the gasoline/air mixture, propane/air mixture, and ethylene/air mixture. It proved to be successful in quenching the flashback flame from all three fuel/air combinations. During the testing with ethylene/air mixtures, there was evidence of slight pressure spiking in the facility piping 25 seconds after ignition and concurrent with the lean blowout of the flame holding on the downstream face of the arrester. Posttest inspection of the arrester revealed no damage to the screen wire, but there was discolorationindicating that the impinging ethylene/air flame had heated the screen above 550°C (1022°F).

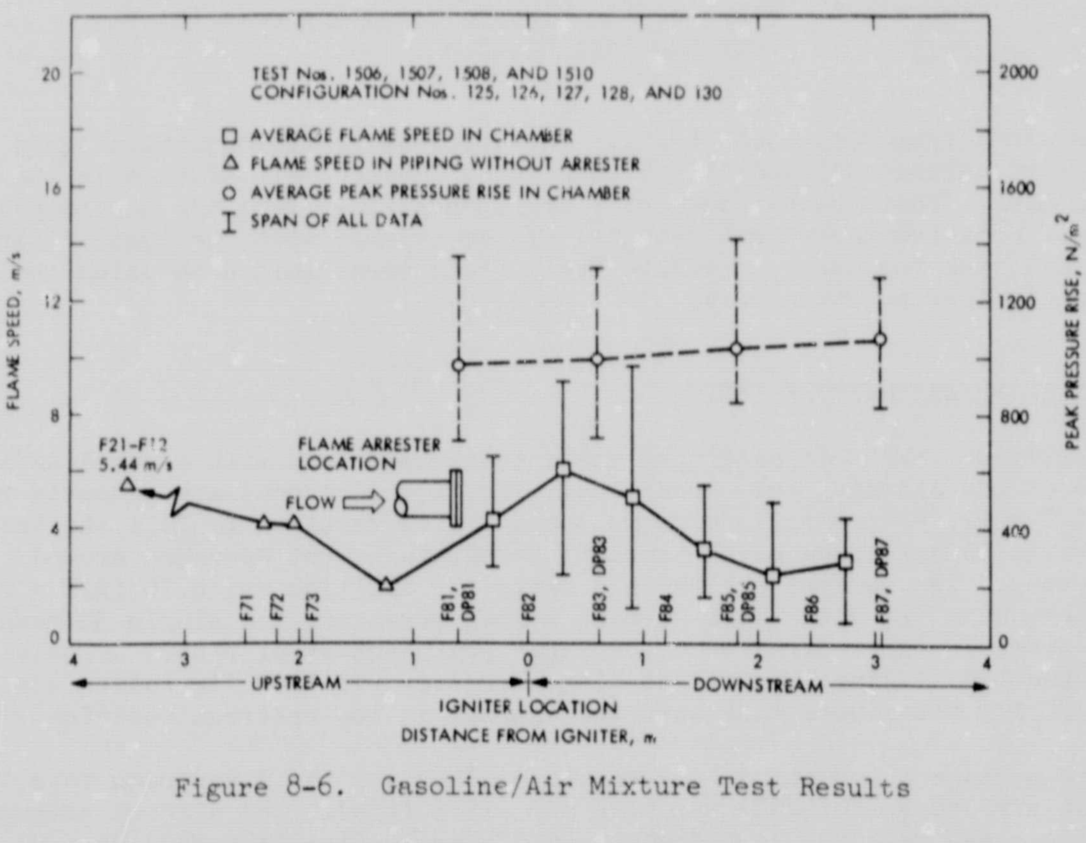


Figure 8-6. Gasoline/Air Mixture Test Results

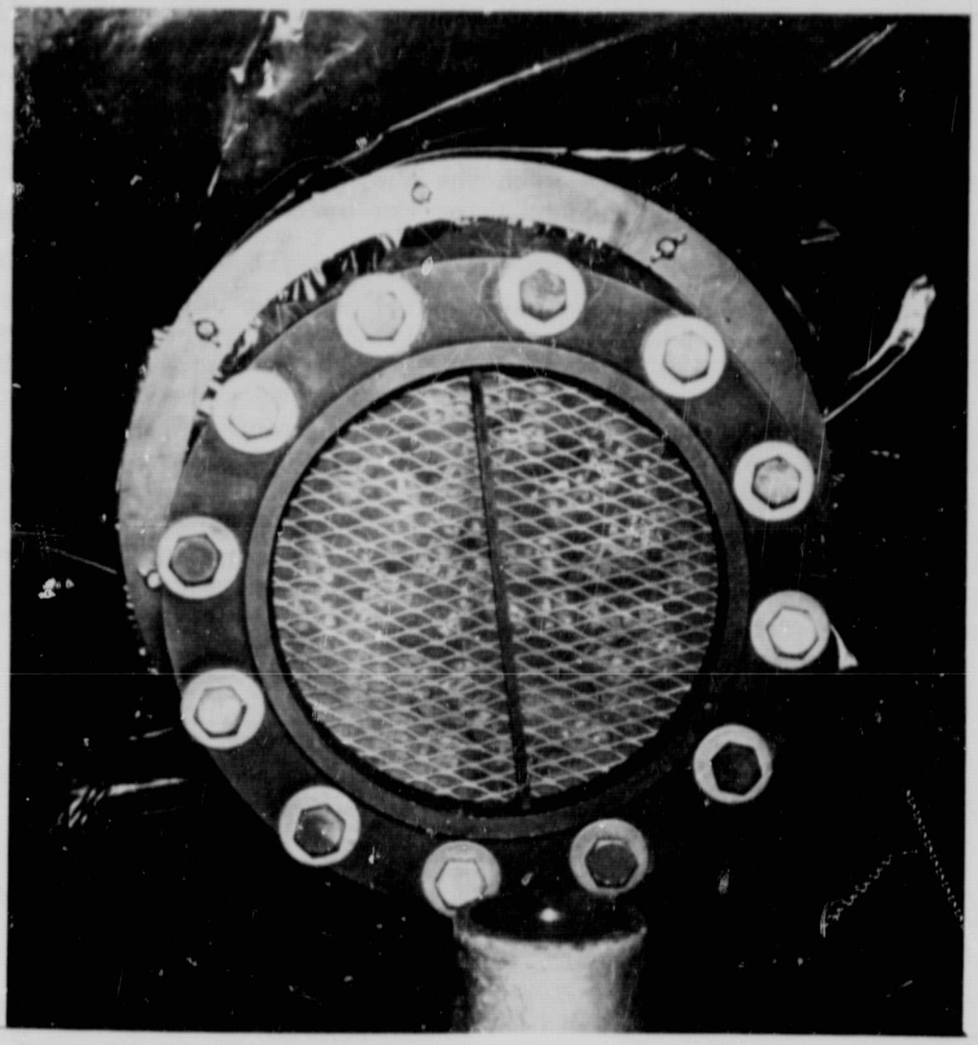


Figure 8-7. Packed Bed of Rings Arrester with Single 30-Mesh Screen and Grid Retainer Test Assembly

The crimped ribbon arrester (Test Configuration Nos. 123 and 124) was also evaluated with the propane/air mixture and ethylene/air mixture while they were present in the fuel system. It also proved successful in quenching all flashback flames from these fuel/air mixtures.

The tests described above completed the NASA funded portion of flashback flame tests on the crimped ribbon and packed bed arrester configurations. The alternate fuels tests using the two screen-type flame arrester configurations with five additional fuel/air mixtures were funded by the U.S. Coast Guard.

E. METHANOL/AIR MIXTURE TESTS

The second series of alternate fuels tests was made with methanol/air mixture at standard test conditions. The injection equivalence ratio was 1.01 (A/F = 6.41) for maximum flame speed. Time required to fill the test chamber averaged 1060 seconds, because of the cold ambient temperatures and the low volatility of methanol. The nominal measured equivalence ratio at ignition was 0.69 (A/F = 9.38). Tests were made with the dual 20-mesh screen arrester and the single 30-mesh screen arrester using the upstream igniter position (Test Configuration Nos. 133 to 135).

The average flame speed between the igniter and the downstream face of the test arresters (F81-F82) was 4.35 m/s (14.3 ft/s). The highest average flame speed measured just downstream of the igniter (F82-F83) was 5.52 m/s (18.1 ft/s). Two flame sensors at the exit of the flame chamber (F86 and F87) were inoperative due to weather conditions. The average peak pressure rise in the chamber was 831 N/m^2 (0.120 psid). Without an arrester installed, the flashback flame entered the facility piping with a flame speed of only 2.19 m/s (7.2 ft/s), and was unable to propagate upstream through the facility piping. A plot of the results from these tests is shown in Figure 8-8. Both the dual 20-mesh screens arrester and the single 30-mesh screen arrester were successful in quenching all flashback flames from the methanol/air mixture.

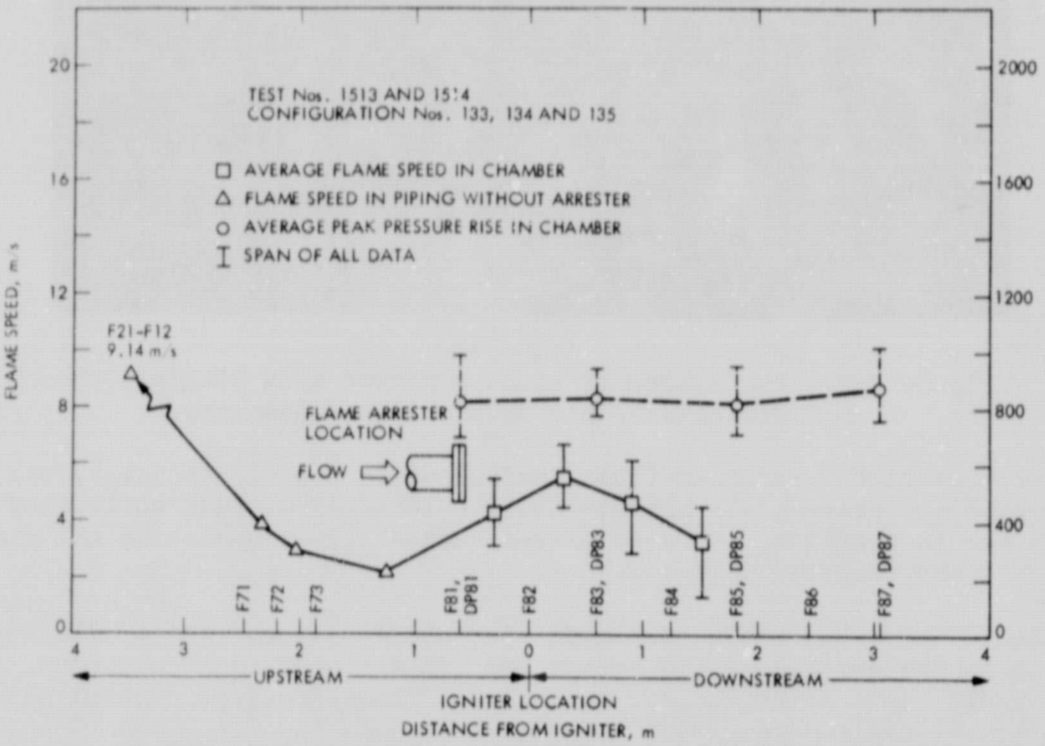


Figure 8-8. Methanol/Air Mixture Test Results

F. TOLUENE/AIR MIXTURE TESTS

The third series of alternate fuels tests were made with toulene/air mixture at standard test conditions. The injection equivalence ratio was 1.05 (A/F = 12.86) for maximum flame speed. Time required to fill the test chamber averaged 1070 seconds. The nominal measured equivalence ratio at ignition was 0.68 (A/F = 19.9). Tests were made with the dual 20-mesh screen arrester and the single 30-mesh screen arrester using the upstream igniter position (Test Configuration Nos. 136 to 138).

The average flame speed between the igniter and the downstream face of the test arresters (F81-F82) was 5.42 m/s (17.8 ft/s). The highest average flame speed measured just downstream of the igniter (F82-F83) was 6.27 m/s (20.6 ft/s); from there it decelerated to only 2.65 m/s (8.7 ft/s) at the flame chamber exit (F86-F87). The average peak pressure rise in the chamber was 668 N/m^2 (0.098 psid), the lowest value recorded for all fuel/air mixtures. Without a flame arrester installed, the flashback flame entered the facility piping with a flame speed of only 0.61 m/s (2.0 ft/s) and was unable to propagate upstream through the facility piping. A plot of the results from these tests is shown in Figure 8-9. Both the dual 20-mesh screen arrester and the single 30-mesh screen arrester were successful in quenching all flashback flames from the toluene/air mixtures.

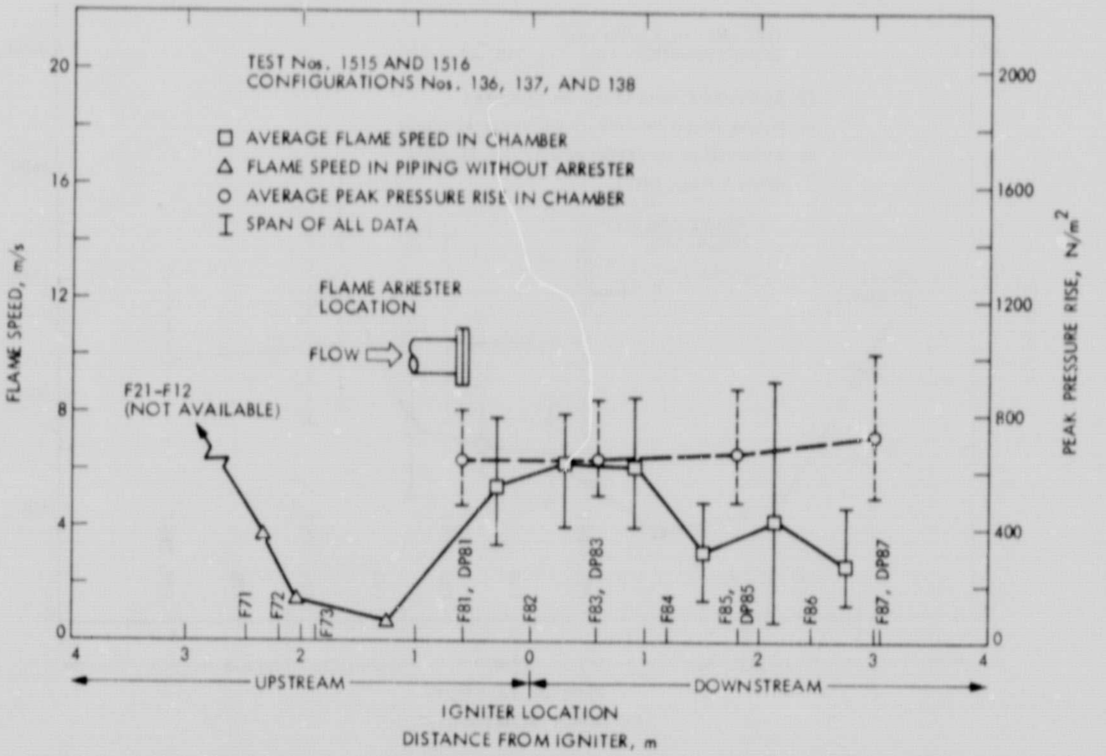


Figure 8-9. Toluene/Air Mixture Test Results

G. DIETHYL ETHER/AIR MIXTURE TESTS

The fourth series of alternate fuels tests were made with diethyl ether/air mixture at standard test conditions. The injection equivalence ratio was 1.15 (A/F = 9.73) for maximum flame speed. Time required to fill the test chamber averaged 580 seconds. The nominal measured equivalence ratio at the time of ignition was 0.71 (A/F = 15.8). Tests were made with the dual 20-mesh screen arrester and the single 30-mesh screen arrester using the upstream igniter position (Test Configuration Nos. 139 to 141).

The average flame speed between the igniter and the downstream face of the test arrester (F81-F82) was 5.61 m/s (21.4 ft/s). The highest average flame speed measured in the center of the chamber (F84-F85) was 11.95 m/s (39.2 ft/s). These flame speeds were the second highest obtained, next to the ethylene/air mixture. The average peak pressure rise in the chamber was 937 N/m^2 (0.136 psid). Without an arrester installed, the flashback flame entered the facility piping with a flame speed of 2.98 m/s (9.78 ft/s) and propagated upstream accelerating to 59.43 m/s (195 ft/s) at the facility inlet arrester (F21-F12). A plot of the results from these tests is shown in Figure 8-10. Both the dual 20-mesh screen arrester and the single 30-mesh screen arrester were successful in quenching all flashback flames from the diethyl ether/air mixture.

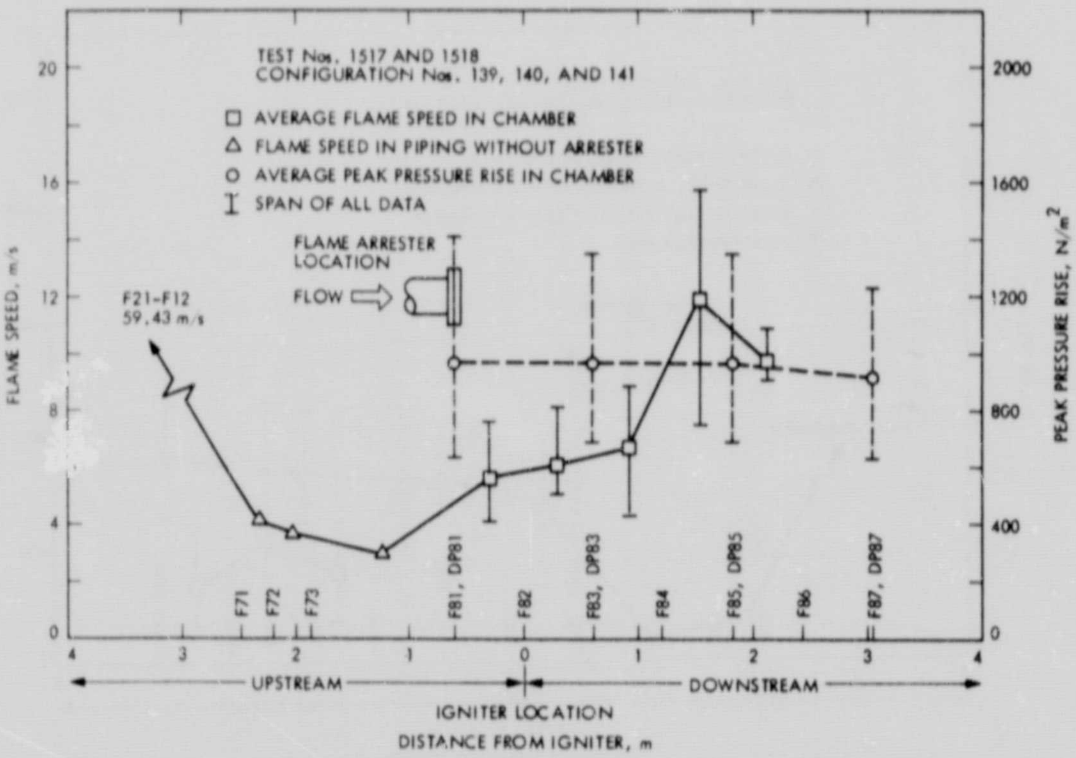


Figure 8-10. Diethyl Ether/Air Mixture Test Results

H. BUTANE/AIR MIXTURE TESTS

The fifth series of alternate fuels tests were made with butane/air mixture at standard test conditions. The injection equivalence ratio was 1.13 (A/F = 13.68) for maximum flame speed. Time required to fill the test chamber averaged 507 seconds. The nominal measured equivalence ratio at the time of ignition was 0.78 (A/F = 19.8). Tests were made with the dual 20-mesh screen arrester and the single 30-mesh screen arrester using the upstream igniter position (Test Configuration Nos. 142 to 144).

The average flame speed between the igniter and the downstream face of the test arrester (F81-F82) was 3.62 m/s (11.9 ft/s). The highest average flame speed measured just downstream of the igniter (F82-F83) was 5.07 m/s (16.6 ft/s); from there it decelerated to only 2.71 m/s (8.9 ft/s) at the flame chamber exit (F86-F87). The average peak pressure rise in the chamber was 926 N/m^2 (0.140 psid). Without an arrester installed, the flashback flame entered the facility piping with a flame speed of 2.26 m/s (7.4 ft/s) and propagated upstream accelerating to 17.54 m/s (57.5 ft/s) at the facility inlet arrester (F21-F12). A plot of the results from these tests is shown in Figure 8-11. Both the dual 20-mesh screen arrester and the single 30-mesh screen arrester were successful in quenching all flashback flames from the butane/air mixtures.

I. ACETALDEHYDE/AIR MIXTURE TEST

The sixth and final series of alternate fuels tests were made with acetaldehydr/air mixture at standard test conditions. The injection equivalence

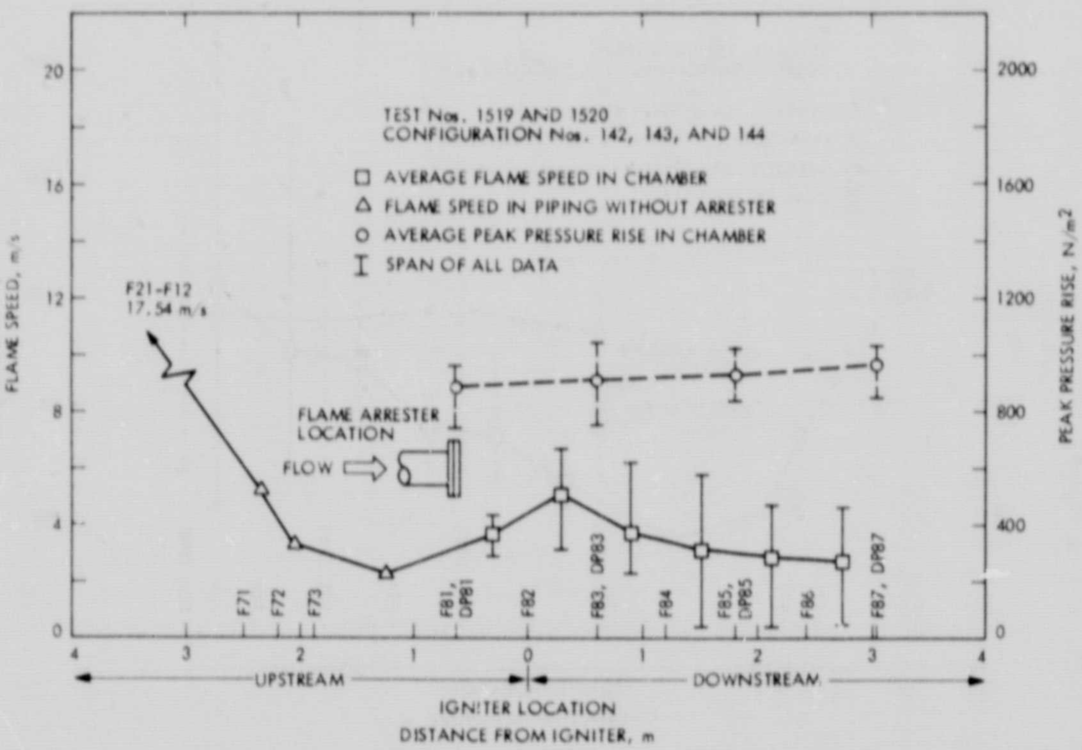


Figure 8-11. Butane/Air Mixture Test Results

ratio was 1.15 (A/F = 6.82) for maximum flame speed. Time required to fill the test chamber averaged 920 seconds. The nominal measured equivalence ratio at the time of ignition was 0.63 (A/F = 12.5). Tests were made with the dual 20-mesh screen arrester and the single 30-mesh screen arrester using the upstream igniter position (Test Configuration Nos. 145 to 147).

The average flame speed between the igniter and the downstream face of the test arrester (F81-F82) was 5.30 m/s (17.4 ft/s). The highest average flame speed measured at the chamber exit (F86-F87) was 12.11 m/s (39.7 ft/s). These flame speeds are about equal to those obtained for the diethyl ether/air mixture. The average peak pressure rise in the chamber was 1102 N/m^2 (0.160 psid), which is the same level obtained with ethylene/air mixture. Without an arrester installed, the flashback flame entered the facility piping with a flame speed of 3.22 m/s (10.6 ft/s) and propagated upstream accelerating to 411 m/s (1348 ft/s) at the facility inlet arrester (F21-F12). A plot of the results from these tests is shown in Figure 8-12. Both the dual 20-mesh screen arrester and the single 30-mesh screen arrester were successful in quenching all flashback flames from the acetaldehyde/air mixture.

J. ARRESTER SELECTION FOR SUSTAINED BURNING TESTS

The tests described above completed the alternate fuel/air mixtures step in the test program logic diagram presented in Figure 8-1. Since both the dual 20-mesh screen arrester and the single 30-mesh screen arrester were successful

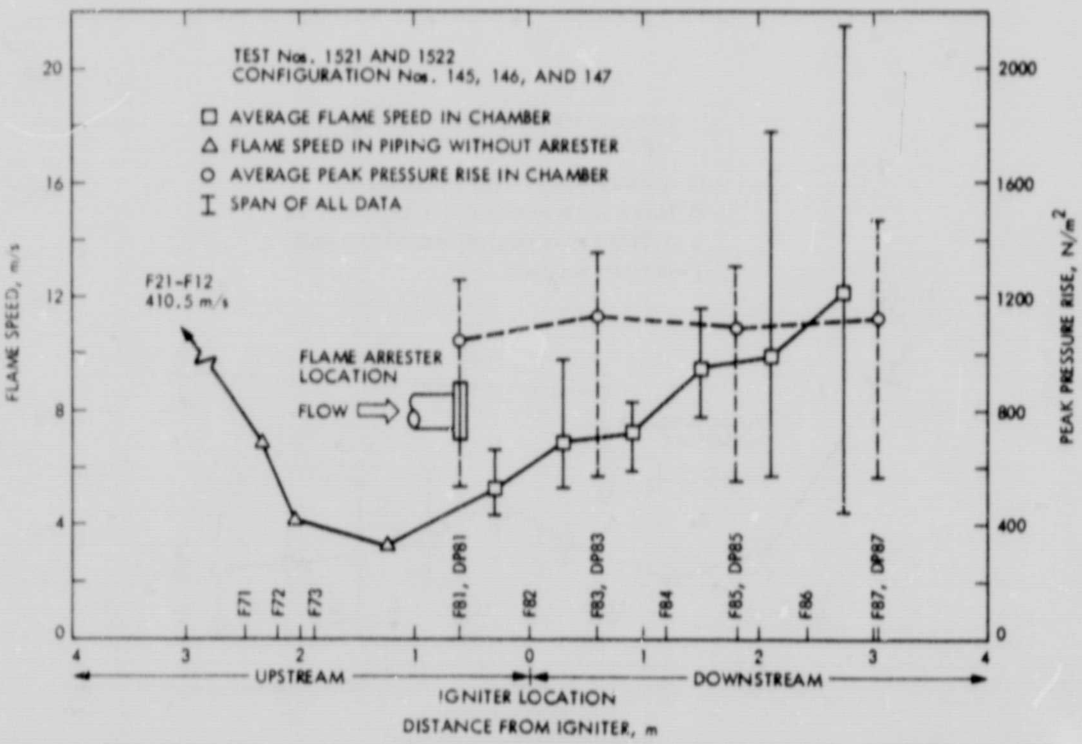


Figure 8-12. Acetaldehyde/Air Mixture Test Results

in quenching all flashback flames from all the alternate fuel tests, they were both designated by the U.S. Coast Guard for sustained burning tests, along with the crimped ribbon arrester and the packed bed arrester for the NASA project.

SECTION IX

SUSTAINED BURNING ARRESTER TESTS

A. PROPANE/AIR MIXTURE TESTS

The first series of sustained burning tests were made with propane/air mixtures at the standard test condition where the injection equivalence ratio was 1.14 (A/F = 13.75). The duration of testing was planned for 30 minutes to allow sufficient time for the test assembly to reach thermal equilibrium. In the event the flame penetrated through the arrester, the test was terminated as quickly as possible to minimize damage to the facility piping and instrumentation.

The dual 20-mesh screen arrester and the single 30-mesh screen arrester were tested in two different test assembly sizes, the original 15.2-cm (6-in.) diameter and a new 25.4-cm (10-in.) diameter. This was done to evaluate the effects of the fuel/air mixture approach velocity and flow-through velocity on the thermal environment at the screens. The spiral-wound, crimped stainless-steel ribbon arrester and the packed bed of Ballast rings arrester were the same configuration that proved successful in the flashback flame testing. All arresters were instrumented with additional thermocouples (Figure 9-1) to measure thermal build-up and to aid in predicting an impending flame penetration when the arrester temperature approached the spontaneous ignition temperature of the fuel/air mixture.

The following results are for the propane/air mixture sustained burning tests. A tabular summary of the test data is presented in Appendix E.

1. Single 30-Mesh Screen Arrester, 15.2-cm Diameter

A schematic drawing of this arrester test assembly (Test Configuration No. 153), presented in Figure 9-2, shows the location of the thermocouple (T8A) used to measure the screen temperature. The small sheath-type thermocouple was mounted with spring loading against the upstream face of the screen. This method was used to maintain point contact and to minimize local flow disturbance. The approaching flow velocity in the 15.2-cm- (6-in.-) diameter pipe adapter housing was 1.5 m/s (5.0 ft/s) and the flow-through velocity in the screen was 4.1 m/s (13.5 ft/s). At the start of testing, the screen temperature reached an initial plateau of 84°C (183°F) after 180 seconds. The temperature continued to increase slowly until it reached 102°C (216°F) after 30 minutes of operation. The sustained flame from the propane/air mixture did not penetrate through the single 30-mesh screen arrester. A plot of the results is presented in Figure 9-3. Posttest inspection of the screen revealed no damage or flame erosion and only slight discoloration of the wire mesh.

2. Dual 20-Mesh Screen Arrester, 15.2-cm Diameter

A schematic drawing of this test assembly (Test Configuration No. 154), presented in Figure 9-2, shows the location of the thermocouples (T8A and T8B) used to measure the two screen temperatures. The approaching flow velocity in the 15.2-cm- (6-in.-) diameter pipe was 1.5 m/s (5.0 ft/s) and the flow-through velocity in the screens was 3.3 m/s (10.8 ft/s). Temperature on the downstream screen (T8A) reached an initial plateau of 92°C (198°F) after 120 seconds of operation and

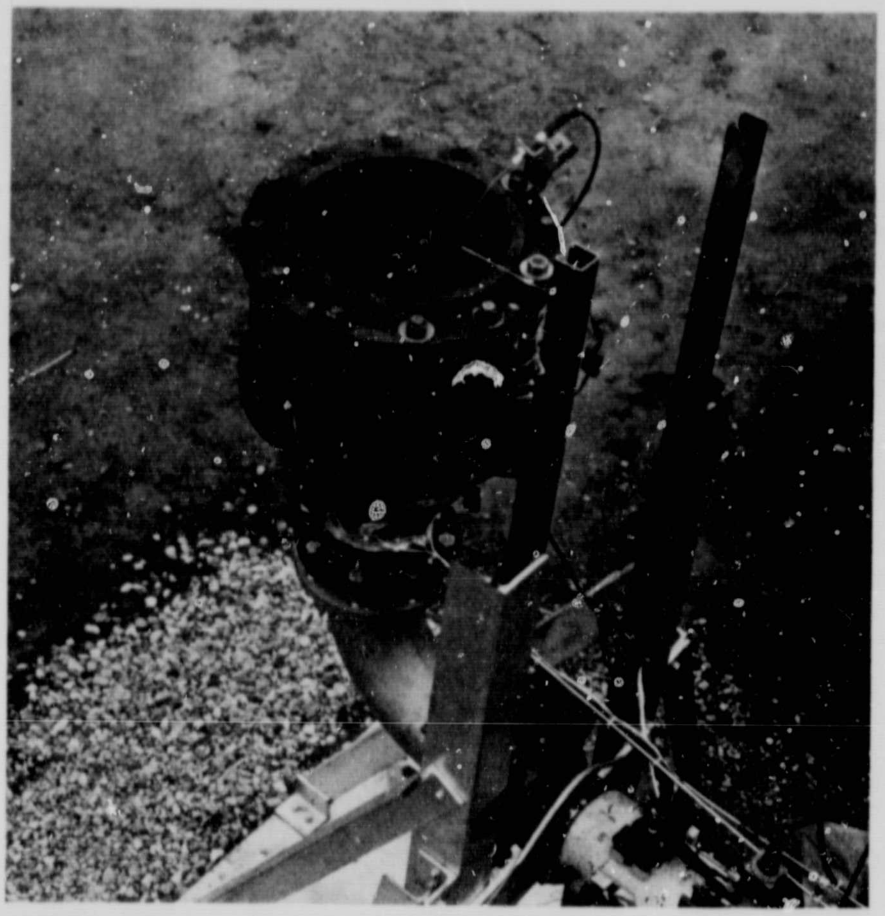


Figure 9-1. Typical Thermocouple Instrumentation Installation for Sustained Burning Tests

then continued to increase slowly until it reached 110°C (230°F) after 30 minutes of operation. The temperature on the upstream screen (T8B) experienced a similar transition, only the levels reached were 50% lower. The propane/air mixture flame did not penetrate through the dual 20-mesh screen arrester. A plot of the test results is presented in Figure 9-4. Posttest inspection of the screens revealed only slight discoloration of the downstream wire mesh.

3. Single 30-Mesh Screen Arrester, 25.4-cm Diameter

A schematic drawing of this arrester test assembly (Test Configuration No. 155), presented in Figure 9-5, shows the location of the thermocouple (T8A) used to measure the screen temperature. The approaching flow velocity in the 25.4-cm- (10-in.-) diameter pipe was 0.56 m/s (1.8 ft/s) and the flow-through velocity in the screen was 1.5 m/s (4.9 ft/s). Temperature on the screen reached an initial high value of 355°C (671°F) after 180 seconds of operation. This temperature did not remain constant due to local wind disturbances, but varied around a nominal value of 325°C (617°F) throughout the full 30 minutes of operation. It appears

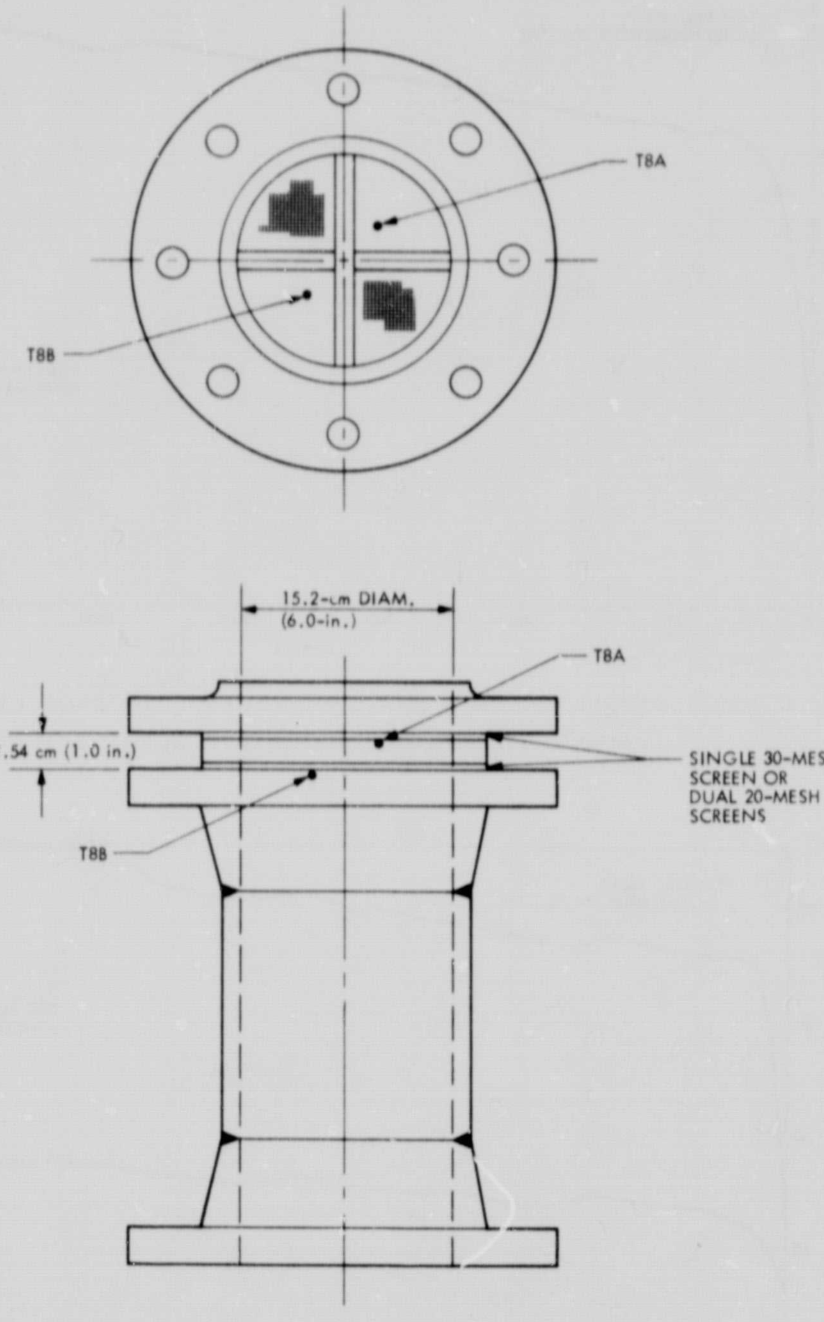


Figure 9-2. Screen-Type Arrester Test Assembly, 15.2-cm Diameter, Schematic Drawing

that the screen temperature varies inversely with the flow-through velocity, as would be expected. The one-third lower flow-through velocity of this larger screen surface resulted in soak-back temperatures three times higher than the smaller screen noted above in Paragraph A-1 of this section. The propane/air

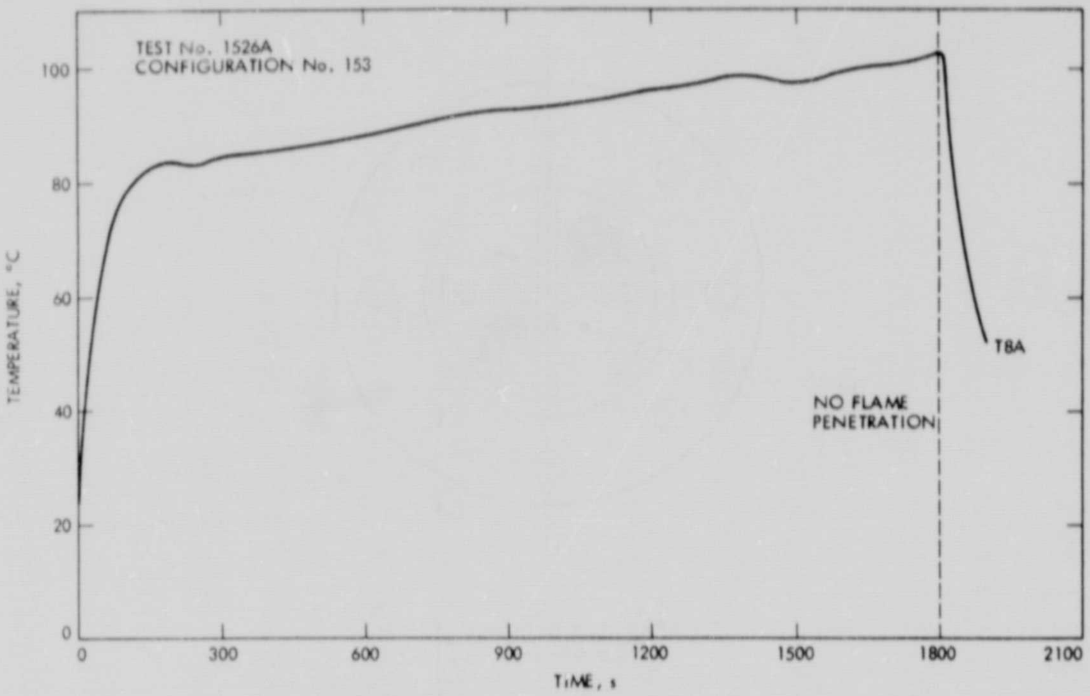


Figure 9-3. Single 30-Mesh Screen Arrester, 15.2-cm Diameter, Propane/Air Mixture Sustained Burning Test Results

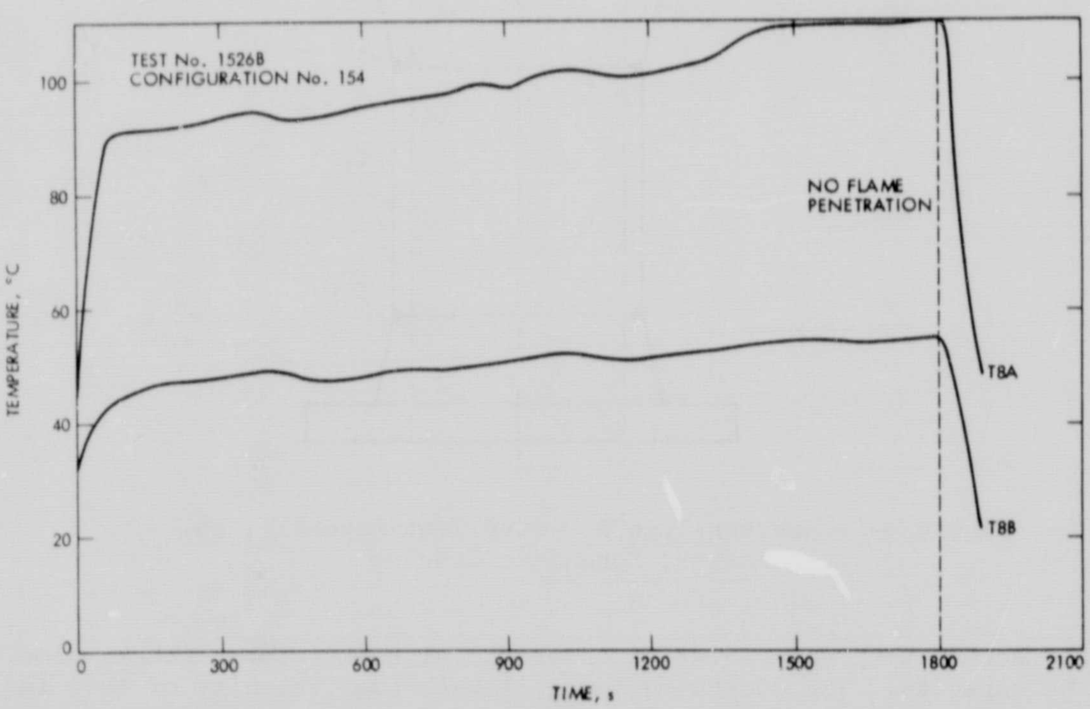


Figure 9-4. Dual 20-Mesh Screen Arrester, 15.2-cm Diameter, Propane/Air Mixture Sustained Burning Test Results

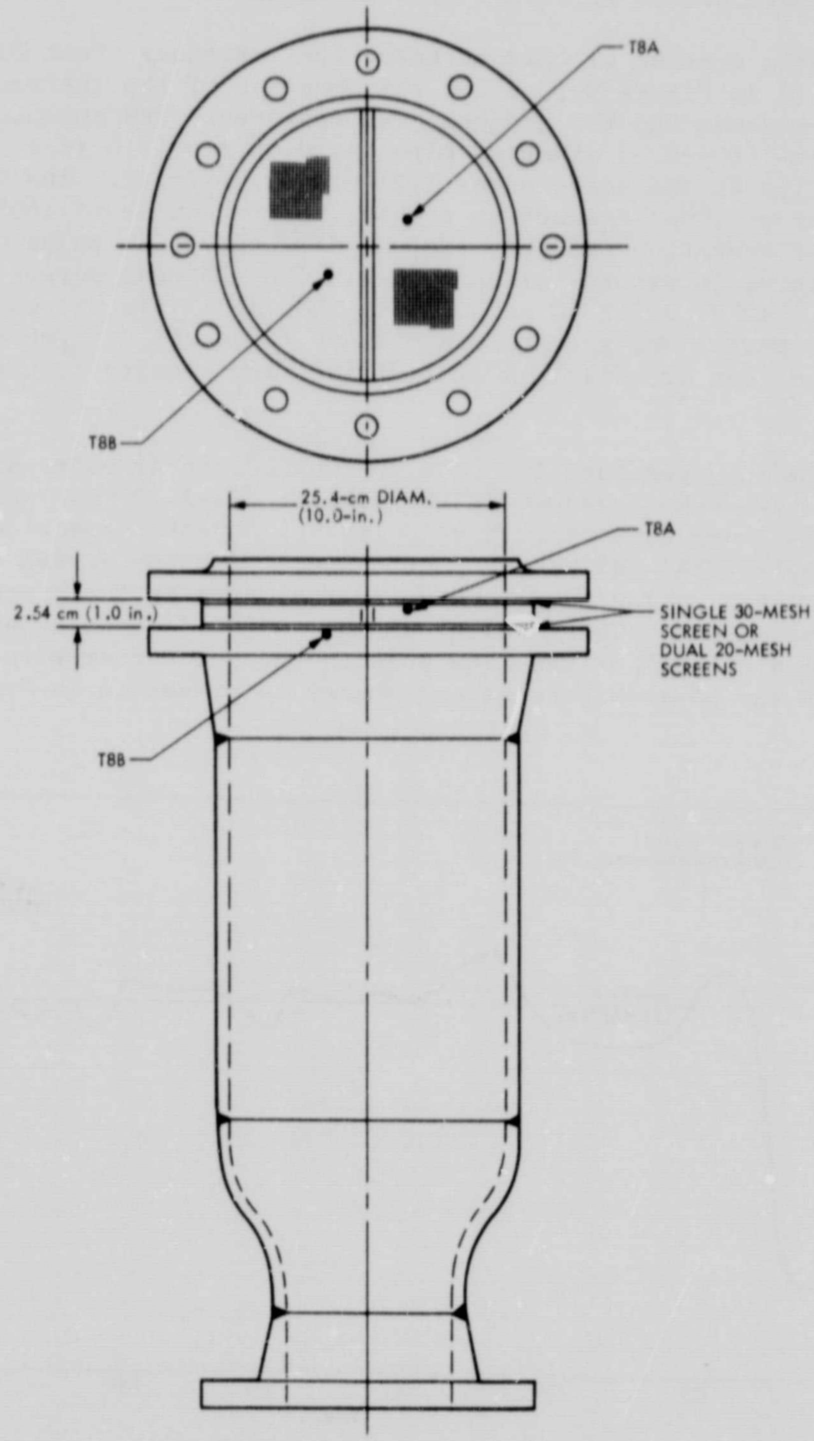


Figure 9-5. Screen-Type Arrester Test Assembly, 25.4-cm Diameter, Schematic Drawing

mixture flame did not penetrate through this single 30-mesh screen arrester. A plot of the test results is presented in Figure 9-6. Posttest inspection revealed only slight discoloration of the wire mesh over about 60% of the surface area as shown in Figure 9-7.

4. Dual 20-Mesh Screen Arrester, 25.4-cm Diameter

A schematic drawing of this arrester test assembly (Test Configuration No. 156), presented in Figure 9-5, shows the location of the thermocouples (T8A and T8B) used to measure the two screens' temperatures. The approaching flow velocity in the 25.4-cm- (10-in.-) diameter pipe was 0.56 m/s (1.8 ft/s) and the flow-through velocity in the screens was 1.21 m/s (3.96 ft/s). The temperature on the downstream screen (T8A) reached an initial plateau value of 160°C (320°F) after 120 seconds of operation and then increased to a nominal value of 190°C (374°F) for the remaining 30 minutes of operation. The upstream screen temperature (T8B) reached 60°C (140°F) after 60 seconds and then slowly increased to 70°C (158°F) by the end of test. The propane/air mixture flame did not penetrate through this dual 20-mesh screen arrester. A plot of the test results is presented in Figure 9-8.

The maximum temperature for this 20-mesh screen arrester assembly was expected to be higher than that measured on the similar sized 30-mesh screen arrester, because of the lower flow-through velocity. Posttest inspection revealed that the thermocouple (T8A) was making poor contact with the screen surface and was located in an area of low temperature, as indicated by the flame impingement pattern on the screen. There was no damage to the screens other than a discoloration covering about 60% of the flow area on the downstream wire mesh. A posttest photograph of the 20-mesh screens and spacer is presented in Figure 9-9.

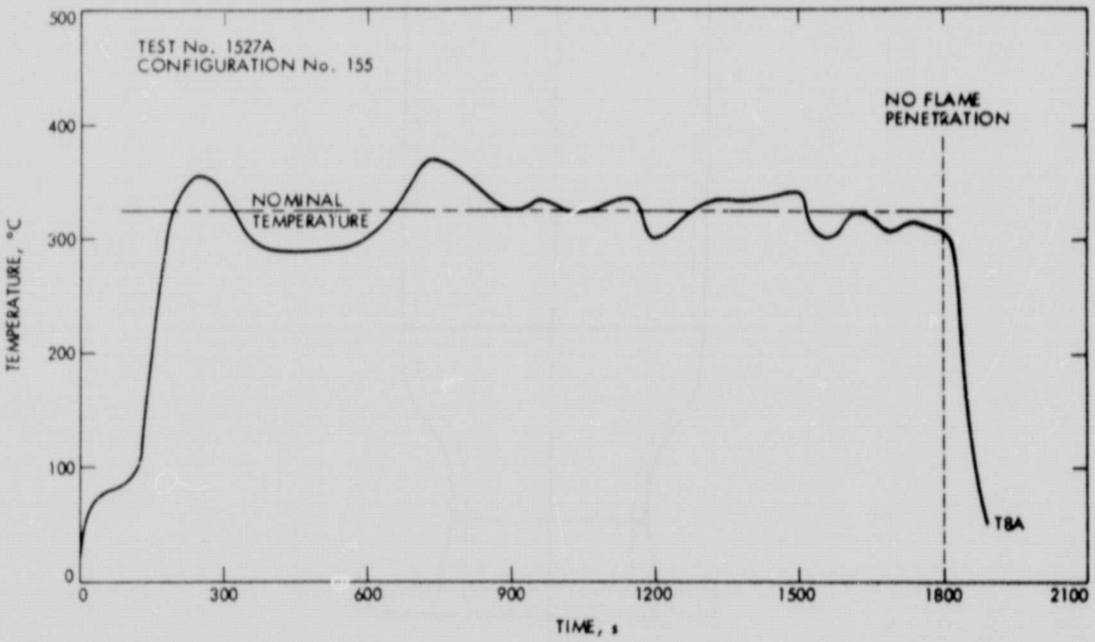


Figure 9-6. Single 30-Mesh Screen Arrester, 25.4-cm Diameter, Propane/Air Mixture Sustained Burning Test Results

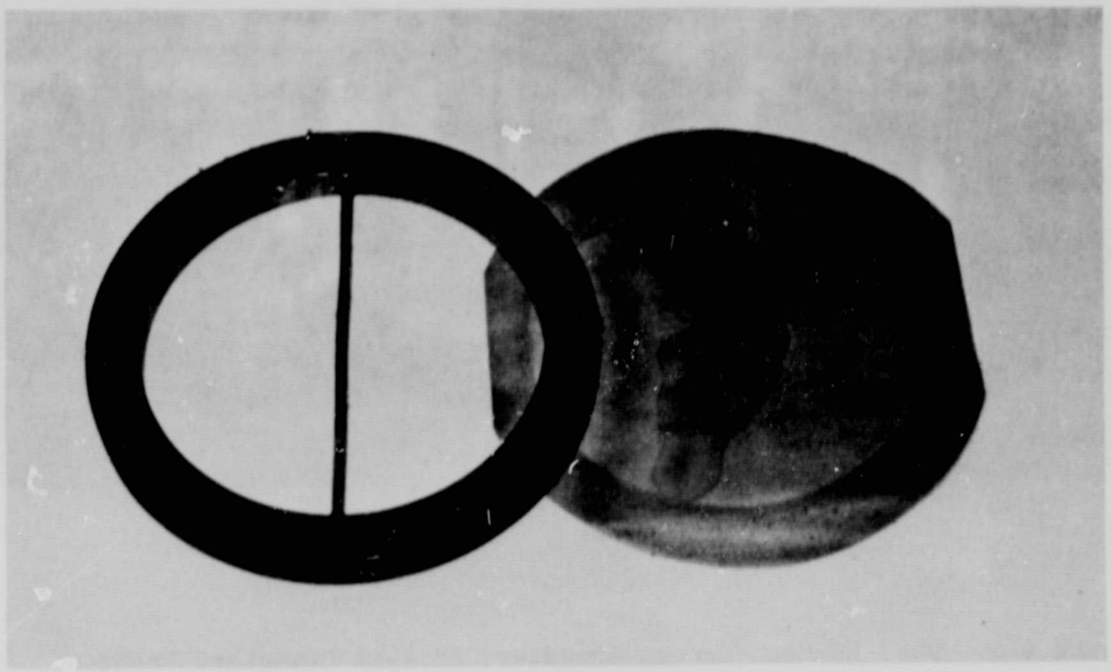


Figure 9-7. Single 30-Mesh Screen Arrester, 25.4-cm Diameter, Posttest

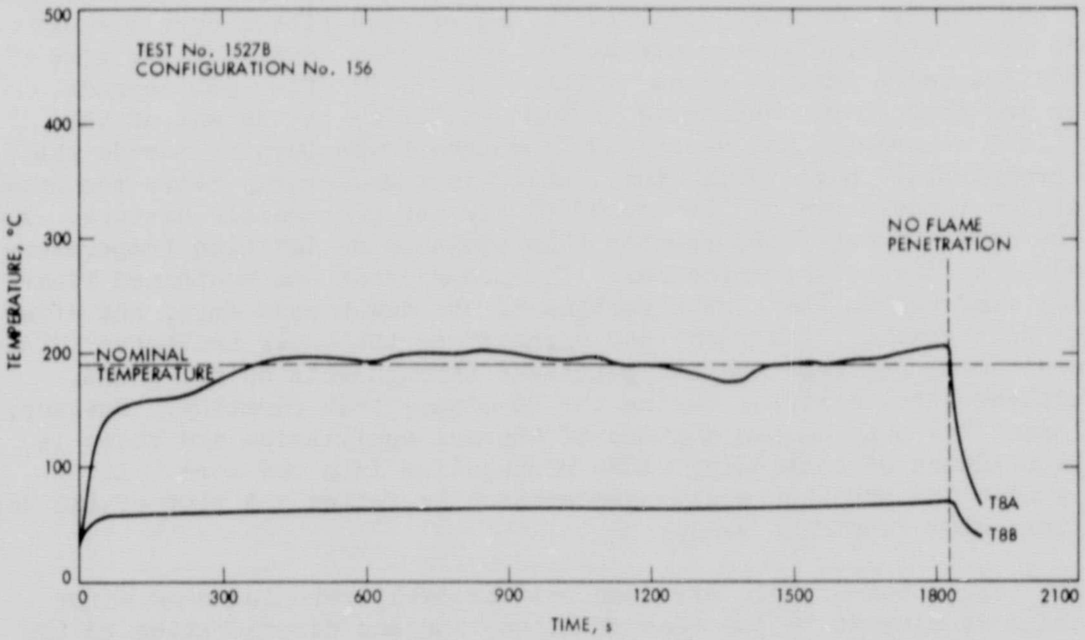


Figure 9-8. Dual 20-Mesh Screen Arrester, 25.4-cm Diameter, Propane/Air Mixture Sustained Burning Test Results

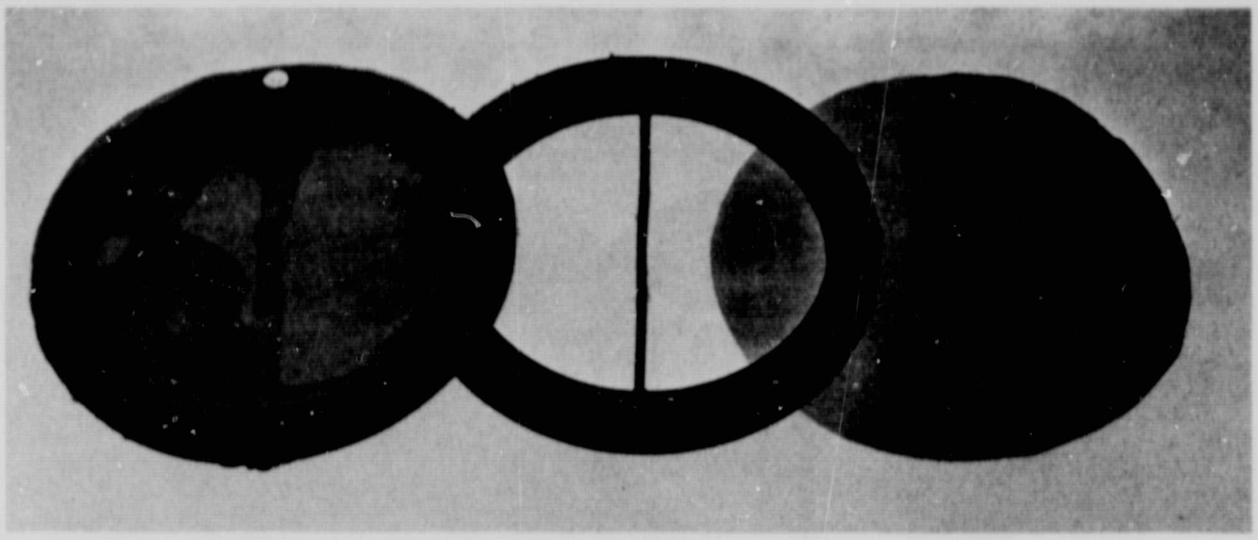
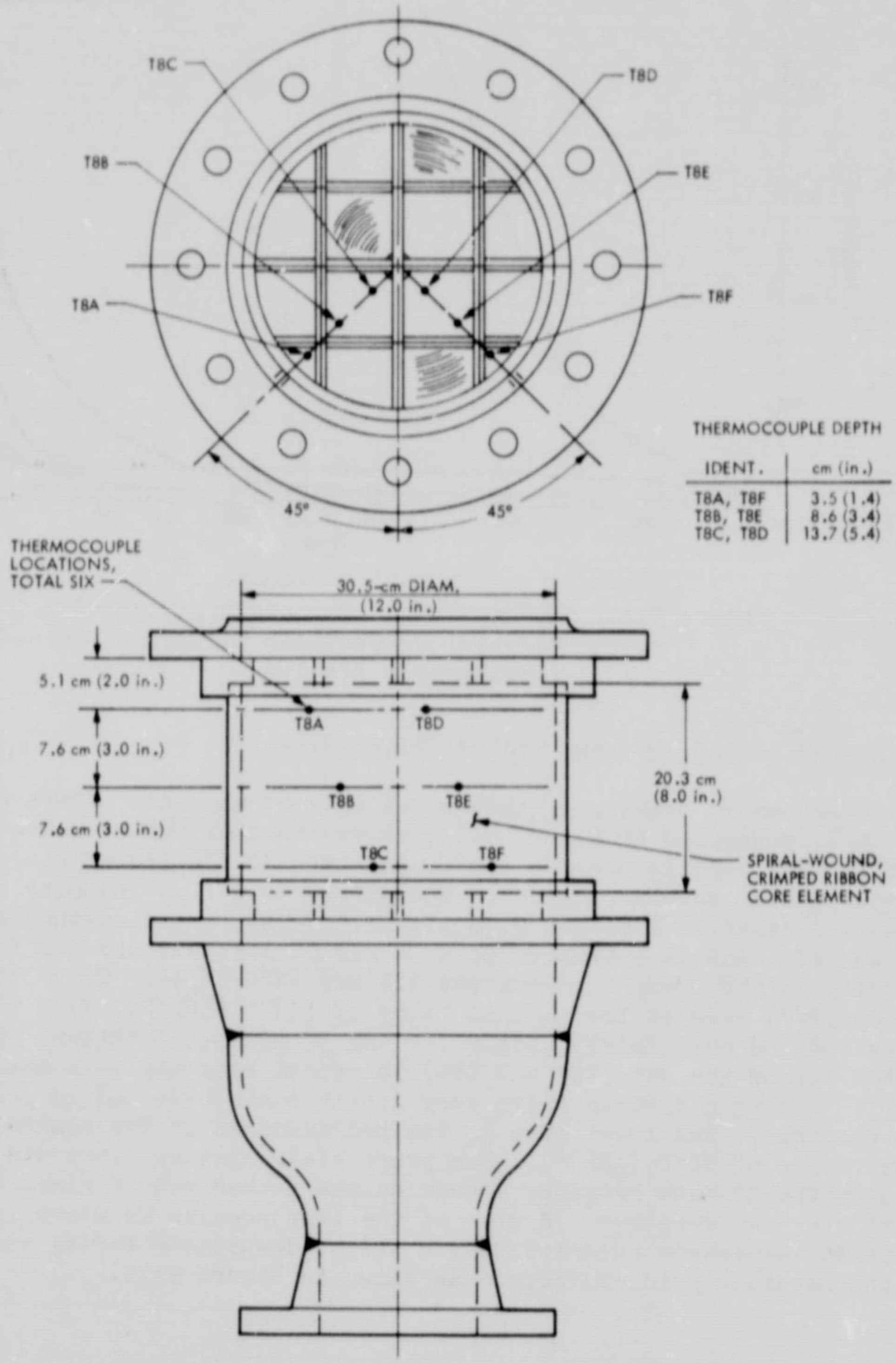


Figure 9-9. Dual 20-Mesh Screen Arrester, 25.4-cm Diameter, Posttest

5. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester

A schematic drawing of this arrester test assembly (Test Configuration No. 149), presented in Figure 9-10 shows the location of the six thermocouples (T8A to T8F) used to measure the crimped ribbon core element temperature. The approaching flow velocity in the 30.5-cm- (12-in.-) diameter pipe was 0.39 m/s (1.28 ft/s) and the flow-through velocity in the crimped ribbon core element was 0.45 m/s (1.46 ft/s). Temperature at the downstream center of the core element (T8D) reached a maximum value of 1000°C (1832°F) after 900 seconds of operation and then slowly decreased to 930°C (1706°F) at the end of the 30 minutes (1800 seconds). The sustained flame had to be burning inside the core element to produce this high temperature, which is considerably above the spontaneous ignition temperature of 504°C (940°F) for the propane/air mixture. The center of the core element (T8B) reached this spontaneous ignition temperature just 30 seconds before test termination. It appears that the sustained flame was initially confined to the center portion of the downstream face, and after 1620 seconds of operation, the flame had expanded to the outer perimeter (T8A). The propane/air mixture flame did not penetrate through this spiral-wound, crimped stainless-steel arrester during the 30-minute test duration. However, the core element had not reached a state of thermal equilibrium and there is considerable evidence of continuing flame propagation into the core. It is quite likely that the arrester would have eventually failed. A plot of the test results is presented in Figure 9-11.

Posttest inspection of this arrester test assembly revealed some minor damage to the core element in the form of distortion and discoloration to the stainless-steel ribbon windings. The retainer grid was also distorted from restricted thermal expansion and some grid elements were broken at the weld joints. A posttest photograph of the downstream end of the arrester assembly is presented in Figure 9-12.



THERMOCOUPLE DEPTH

IDENT.	cm (in.)
T8A, T8F	3.5 (1.4)
T8B, T8E	8.6 (3.4)
T8C, T8D	13.7 (5.4)

Figure 9-10. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester Test Assembly Schematic Drawing

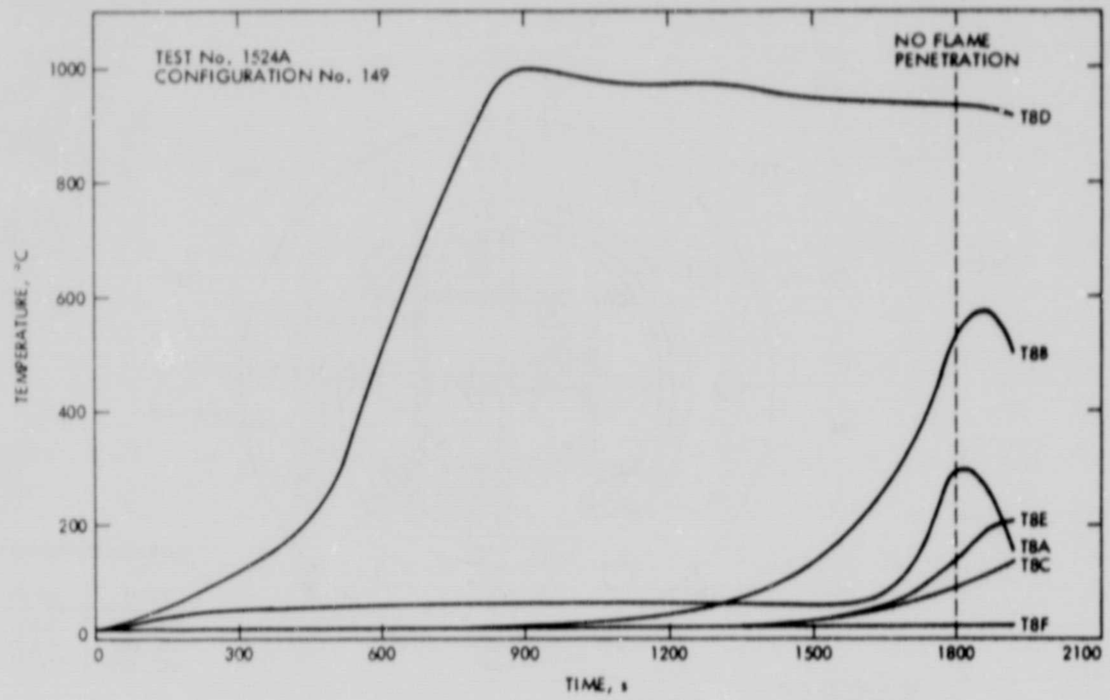


Figure 9-11. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester Propane/Air Mixture Sustained Burning Test Results

6. Packed Bed of Aluminum Ballast Rings Arrester

A schematic drawing of this arrester test assembly (Test Configuration No. 151), presented in Figure 9-13, shows the location of seven thermocouples (T8A to T8G) used to measure the temperature in the bed of rings and on the single 30-mesh screen retainer. The approaching flow velocity in the 25.4-cm-(10-in.-) diameter pipe was 0.56 m/s (1.8 ft/s), the flow-through velocity in the bed of rings is estimated at 0.94 m/s (3.1 ft/s), and the flow-through velocity in the 30-mesh screen was 1.5 m/s (4.9 ft/s). Temperature of the screen (T8G) reached the nominal value of 350°C (662°F) after 200 seconds of operation and held fairly steady for the 30 minutes duration. The temperatures at the top of the bed (T8A and T8D) increased slightly to a maximum of 125°C (257°F) due to radiation only; very little conductive and no convective heating was possible. The lower part of the bed remained at the nominal mixture inlet temperature of 50°C (122°F). The propane/air mixture flame did not penetrate through the 30-mesh retainer screen on the packed bed of rings during the 30-minute test duration. A plot of the test results is shown in Figure 9-14. Posttest inspection revealed only a slight downstream bowing and discoloration of the retainer grid and screen as shown in Figure 9-15.

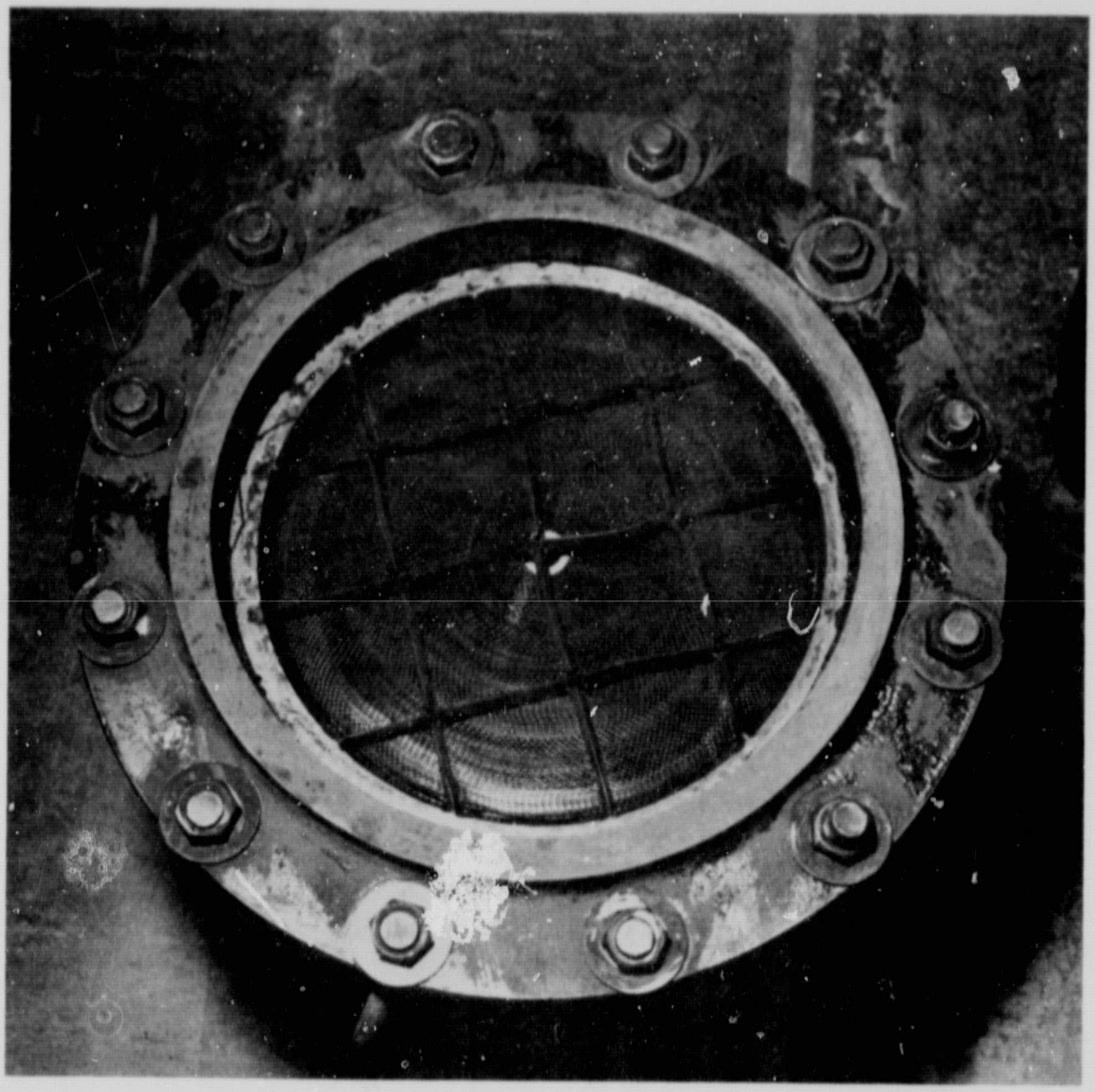


Figure 9-12. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester Downstream End Posttest

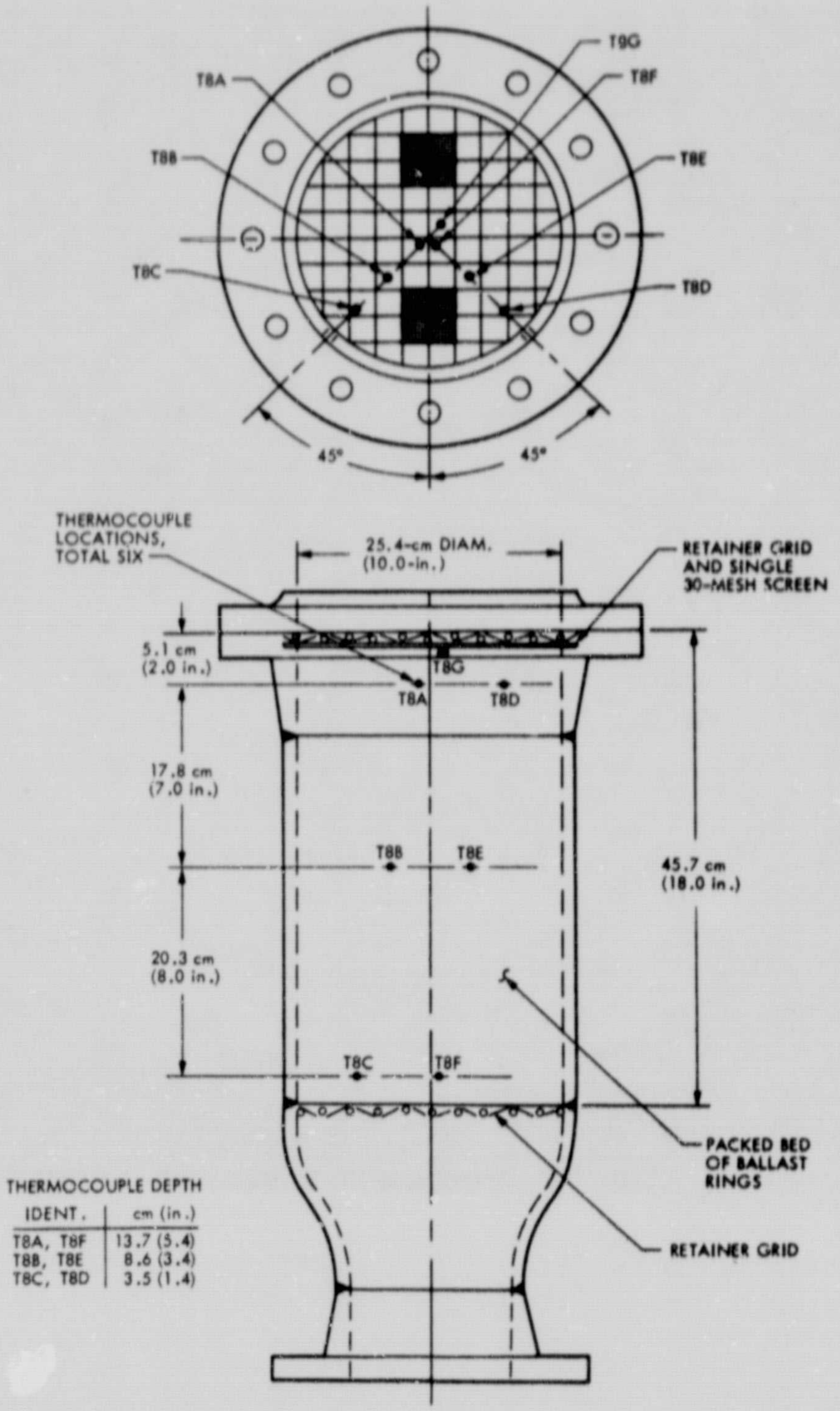


Figure 9-13. Packed Bed of Aluminum Ballast Rings with Single 30-Mesh Screen Arrester Test Assembly Schematic Drawing

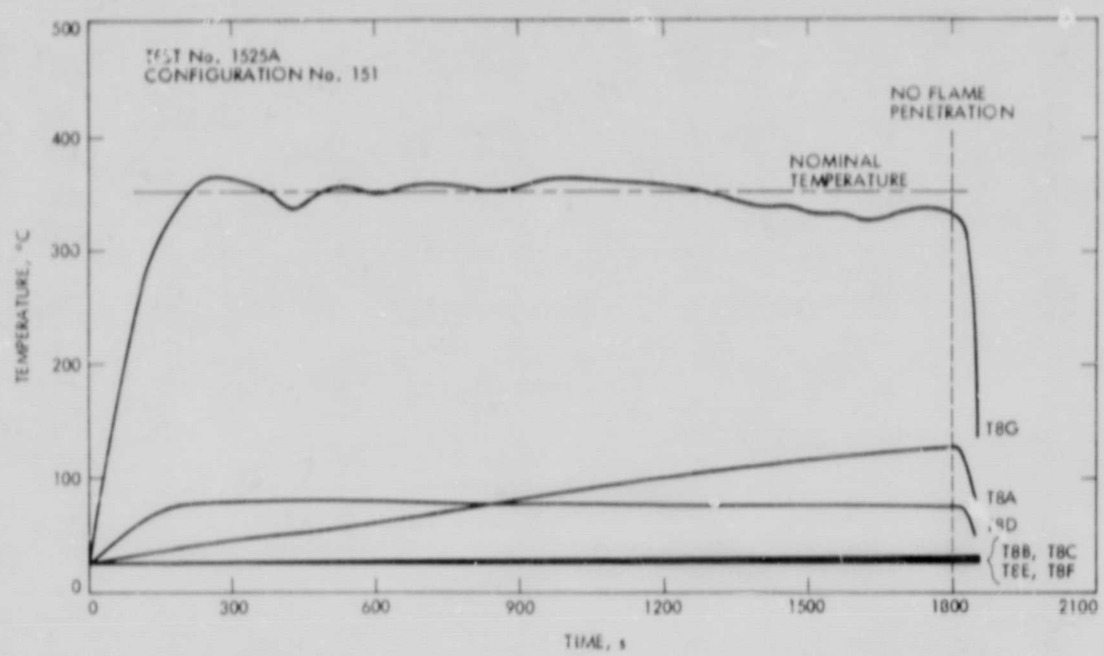


Figure 9-14. Packed Bed of Aluminum Ballast Rings with Single 30-Mesh Screen Arrester Propane/Air Mixture Sustained Burning Test Results

B. ETHYLENE/AIR MIXTURE TESTS

This last series of sustained burning tests were made with ethylene/air mixture at standard test conditions where the injection equivalence ratio was 1.15 (A/F = 12.86). The planned test duration was 30 minutes. Only the two arrester configurations of the NASA funded program were tested: (1) the spiral-wound, crimped stainless-steel ribbon arrester, and (2) the packed bed of aluminum Ballast rings. The USCG funded program did not require sustained burning tests with ethylene/air mixtures because the test conditions were considered to be too severe for screen-type flame arresters.

The following results are for the ethylene/air mixture sustained burning tests. A tabular summary of the test data is presented in Appendix E.

1. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester

This is the same arrester test assembly (Test Configuration No. 150) shown in Figure 9-10. The test flow conditions were the same as those described in Paragraph A-5 of this section. On the first test (No. 1524B) the flame penetrated into the core (T8A and T8E) after only 60 seconds of operation and reached a high temperature of around 900°C (1652°F) at 150 seconds. The flame spread to the outer perimeter of the core (T8B and T8D) increasing this area temperature to

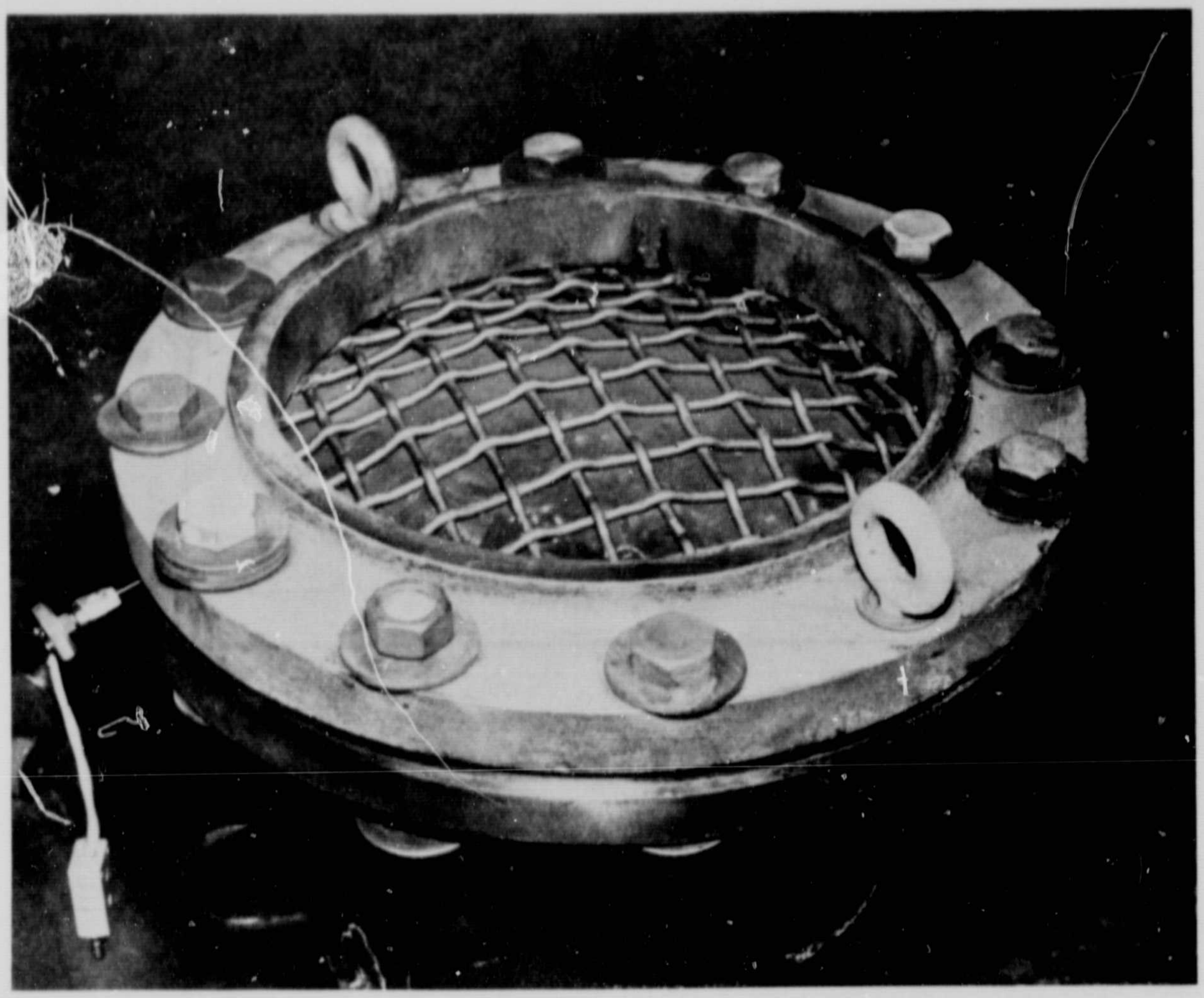


Figure 9-15. Packed Bed of Ballast Rings with Single 30-Mesh Screen Arrester Posttest

900°C (1652°F) after 240 seconds of operation. The flame penetrated through the 20.3-cm (8-in.) depth of the core at 423 seconds, so the test was terminated. Temperature measurements at the upstream end of the core (T8C and T8F) were approaching the spontaneous ignition temperature for ethylene/air mixture of 490°C (914°F) just before flame penetration occurred. A plot of the test results is presented in Figure 9-16. Posttest inspection of the arrester revealed no further distortion and discoloration of the crimped ribbon windings or the retainer grid.

The test described above was repeated at the same test conditions and with the same test assembly. This second test (No. 1524C) produced almost identical results as the first test, only flame penetration occurred earlier at 383 seconds, when the upstream core temperature reached or exceeded the spontaneous ignition temperature for the ethylene/air mixture. A plot of the test results is presented in Figure 9-17. Posttest inspection showed no further change to the arrester test assembly.

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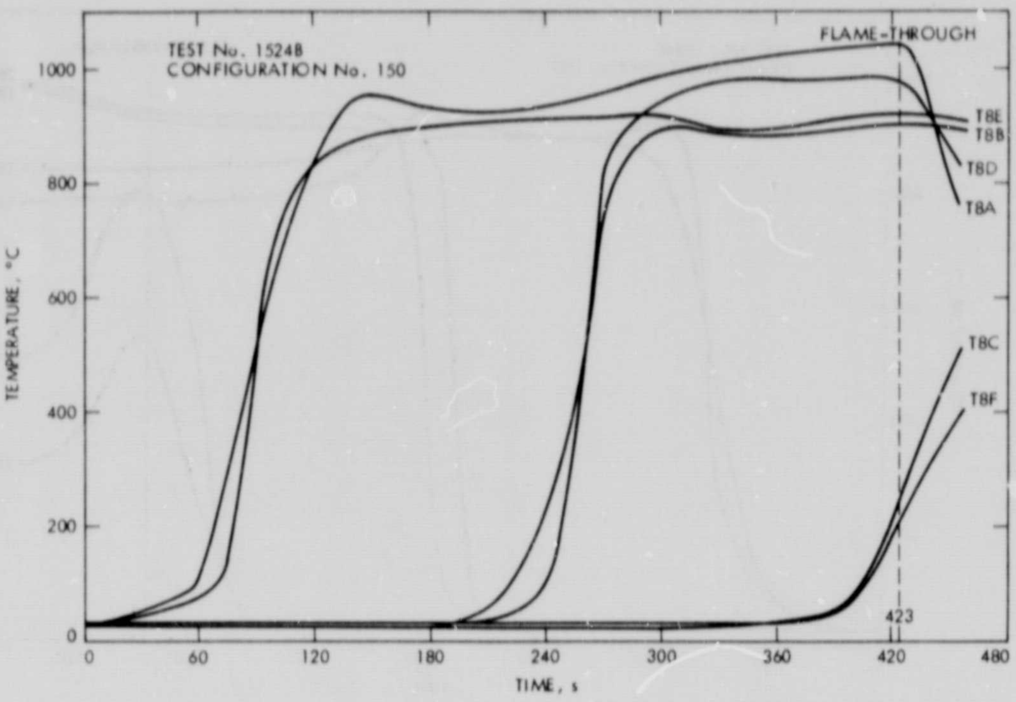

Figure 9-16. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester Ethylene/Air Mixture Sustained Burning First Test Results

2. Packed Bed of Aluminum Ballast Rings Arrester

This is the same arrester test assembly (Test Configuration No. 152) shown in Figure 9-13. The test flow conditions were the same as those described in Paragraph A-6 of this section. In the first test (No. 1525B) the temperature on the upstream face of the retainer screen (T8G) increased rapidly, reaching the spontaneous ignition level of 490°C (914°F) after only 35 seconds of operation. Flame penetration occurred at 43 seconds when the screen temperature reached 560°C (1040°F). The bed of aluminum Ballast rings remained at the inlet ethylene/air mixture temperature with only the downstream center of the bed (T8A) receiving any measurable radiation from the sustained burning. Flame penetration through the retainer screen was followed by a detonation in the inlet piping. Flame speeds measured in the witness section, which was just upstream of the test arrester section, were at the detonation velocity of around 1830 m/s (6000 ft/s). This would indicate that the penetrating flame had made the transition from deflagration to detonation within the length of the packed bed arrester. A plot of the test results is presented in Figure 9-18. Posttest inspection of the arrester revealed some distortion and discoloration of the retainer grid and screen assembly caused by internal pressure developed during the detonation.

The above test was repeated at the same test conditions and with the same arrester test assembly. This second test (No. 1525C) resulted in a detonation immediately after ignition. Posttest disassembly and inspection of the packed bed arrester revealed that the screen retainer had been impacted in several

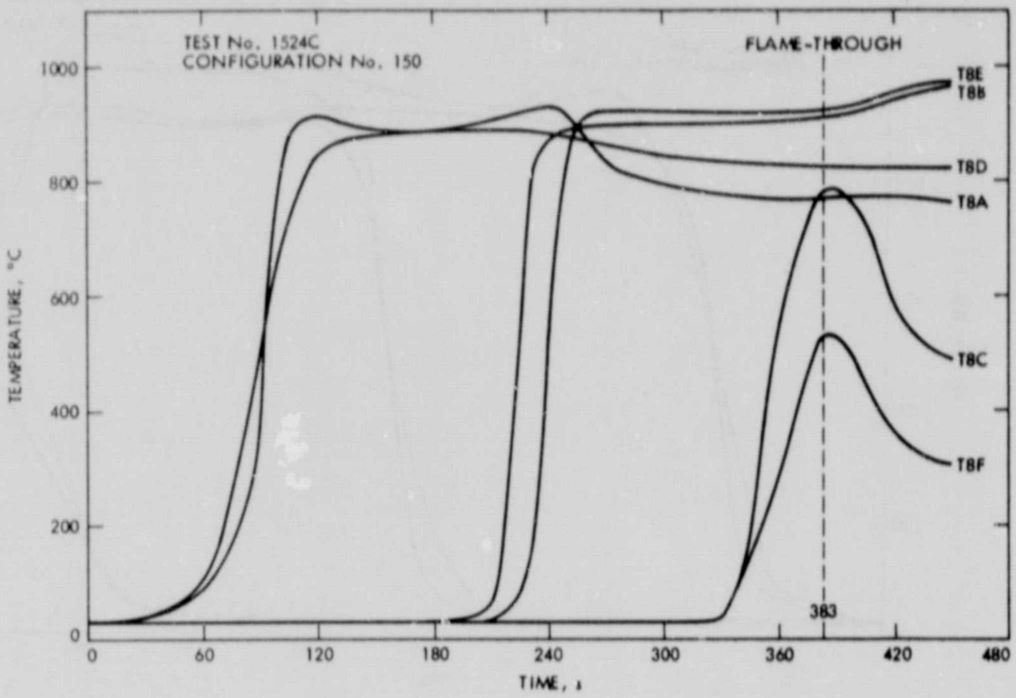

Figure 9-17. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester Ethylene/Air Mixture Sustained Burning Second Test Results

places by Ballast rings causing punctures as shown in Figure 9-19. The undetected damage to the screen was probably initiated to a lesser extent during the first sustained burning test that resulted in a detonation. These small punctures allowed flame penetration without heat-up on the second test and the subsequent detonation enlarged the holes to the size shown.

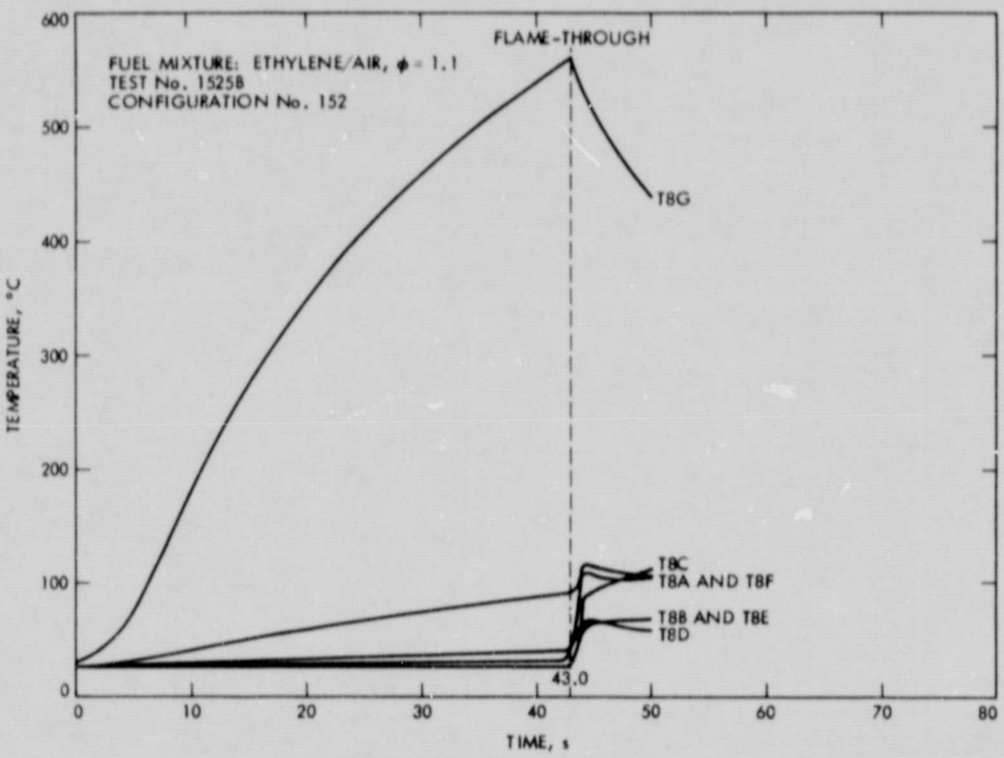

Figure 9-18. Packed Bed of Ballast Rings with Single 30-Mesh Screen Arrester Ethylene/Air Sustained Burning Test Results

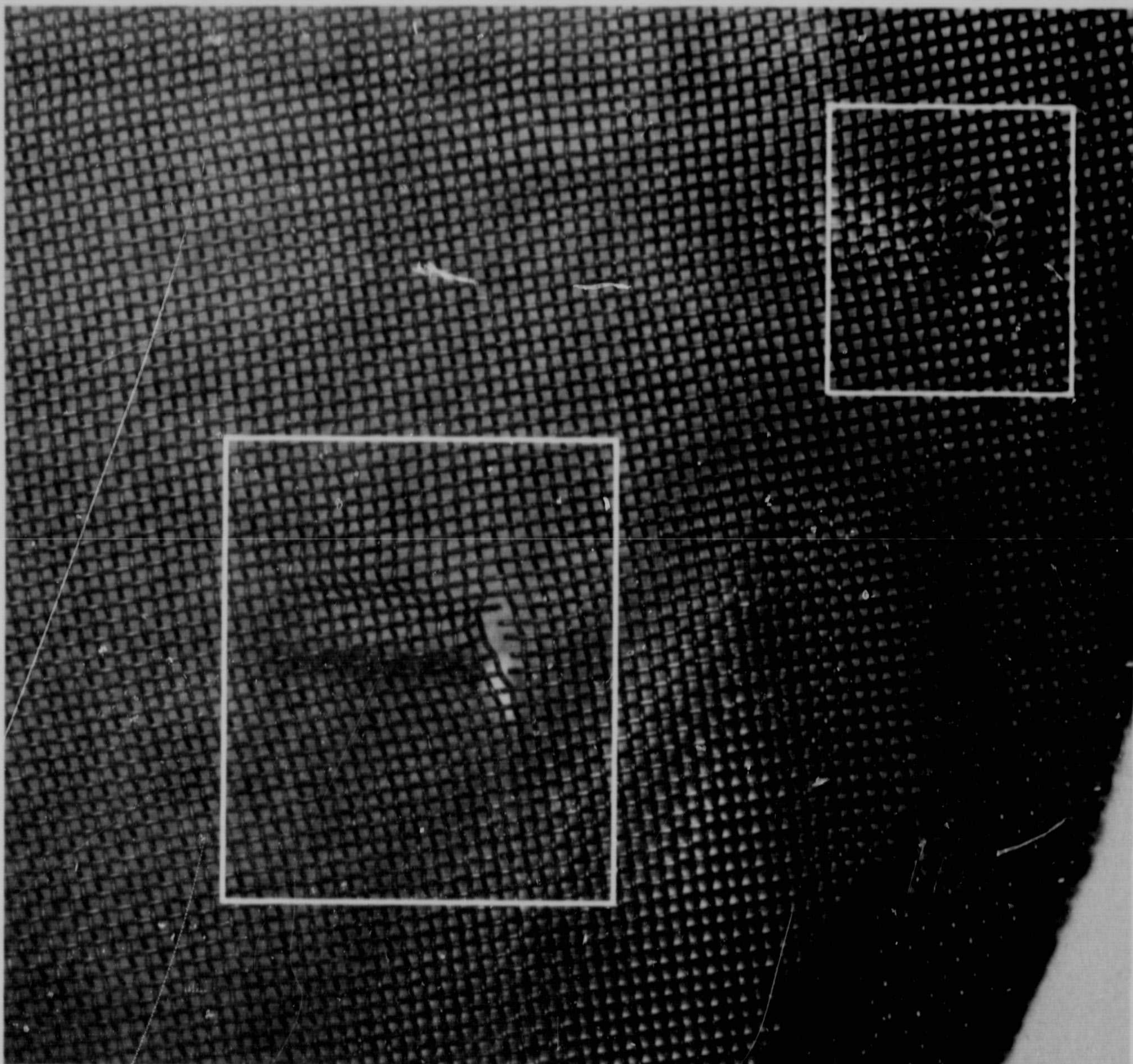

Figure 9-19. Single 30-Mesh Screen Retainer from the Packed Bed of Ballast Rings Arrester Posttest

SECTION X

CONCLUSIONS

The following conclusions have been reached from the test results of this experimental evaluation of flame arrester devices in a simulated fuel storage tank vent stack installation discharging eight types of combustible fuel/air mixtures, including: (1) propane, (2) ethylene, (3) gasoline, (4) methanol, (5) toluene, (6) diethyl ether, (7) butane, and (8) acetaldehyde. The test flame arresters were mounted on the end of a 15.2-cm- (6-in.-) diameter pipe vent located in an unconfined one-atmosphere environment. The standard test condition used an injection equivalence ratio from 1.0 to 1.2 to produce the theoretical maximum flame speed for the particular fuel/air mixture in use; the fuel/air mixture temperature ranged from 10 to 38°C (50 to 100°F), and the inlet piping nominal flow velocity was 1.52 m/s (5 ft/s).

(1) An ignition source upstream near the flame arrester and in the center of the exhaust plume produced the highest flashback flame speed for a flame propagating upstream in the direction of the arrester.

(2) Ethylene/air mixture produced the highest average flashback flame speed of 6.60 m/s (21.65 ft/s), ranging from 4.86 to 10.66 m/s (15.94 to 34.98 ft/s).

(3) Butane/air mixture produced the lowest average flashback flame speed of 3.62 m/s (11.88 ft/s), ranging from 2.92 to 4.25 m/s (9.58 to 13.94 ft/s).

(4) Flashback flames from the typical bulk cargo fuels tested will propagate in an open environment, such as the deck of a transport vessel, but will not produce a detonation unless they penetrate an opening leading into a fuel cargo tank.

(5) The single 30-mesh stainless-steel screen arrester was effective in quenching flashback flames from all eight fuel/air mixtures tested.

(6) The dual 20-mesh stainless-steel screen arrester was effective in quenching flashback flames from all eight fuel/air mixtures tested except the ethylene/air mixture, where the flame speed was 4.86 m/s (15.94 ft/s) or faster.

(7) Damage to a screen flame arrester from a puncture, tear, or corrosion that results in holes larger than the original mesh size renders the screen useless in quenching a flashback flame. The damaged screen should be replaced to restore the arrester's effectiveness.

(8) The spiral-wound, crimped stainless-steel ribbon arrester was effective in quenching flashback flames from the propane, ethylene, and gasoline fuel/air mixtures tested, and would probably quench the other five fuel/air mixtures listed.

(9) The packed bed of aluminum Ballast rings arrester with single 30-mesh stainless-steel screen retainers was effective in quenching flashback flames from the propane, ethylene, and gasoline fuel/air mixtures tested, and would probably quench the other five fuel/air mixtures listed.

(10) The packed bed of aluminum Ballast rings arrester without the single 30-mesh screen retainer was not effective in quenching flashback flames from gasoline/air mixtures, and would probably not quench the other seven fuel/air mixtures listed.

(11) The test configurations for the single 30-mesh screen arrester, the dual 20-mesh screen arrester, the spiral-wound, crimped ribbon arrester, and the packed bed of Ballast rings arrester withstood all flashback flame testing without any structural damage and only slight discoloration from the short duration of flame impingement (approximately 25 seconds).

(12) The single 30-mesh screen arrester and the dual 20-mesh screen arrester withstood flames from propane/air mixtures for 30 minutes without structural damage and only slight discoloration of the screen wire. The fuel/air mixture flow velocity through the openings in the screen ranged from 1.2 to 4.1 m/s (3.9 to 13.5 ft/s), depending on the size of the arrester test assembly. In each configuration, the screens reached a condition approaching thermal equilibrium after approximately 300 seconds where the temperature was well below the spontaneous ignition temperature for the propane/air mixture. It is concluded that the sustained burning conditions on these arresters could have continued for an indefinite period of time.

(13) The equilibrium temperature on the surface of a screen flame arrester at sustained burning conditions is a function of flow velocity of the fuel/air mixture passing through the screen; the lower the velocity, the higher the equilibrium temperature. It is possible that at very low flow-through velocities the temperature of the screen would increase to the spontaneous ignition temperature of the fuel and the flame could penetrate the screen arrester.

(14) The spiral-wound, crimped ribbon arrester withstood flames from the propane/air mixture for 30 minutes. During this time, the flame propagated into part of the depth of the core element, causing distortion and discoloration of the stainless-steel ribbon. Thermal equilibrium within the core element was not achieved during the 30 minutes of testing as the temperatures measured inside the ribbon windings continued to increase above the spontaneous ignition temperature for propane/air mixtures. It is concluded that the flame would have eventually penetrated the arrester, given sufficient time. Sustained burning from the ethylene/air mixture did penetrate through this arrester on two tests of 423 and 383 seconds. Therefore, the ability of this type of flame arrester to withstand sustained burning is highly dependent on the flame speed and the spontaneous ignition temperature of the fuel/air mixture.

(15) The packed bed of Ballast rings arrester with a single 30-mesh screen retainer withstood flames from the propane/air mixture for 30 minutes. The results were very similar to those obtained from the single 30-mesh screen arrester, and it is apparent that the bed of rings has little or no influence on the performance of this arrester configuration. Sustained burning from the ethylene/air mixture did penetrate through this arrester in only 43 seconds on one test, resulting in a deflagration-to-detonation transition within the bed of rings. The retainer screen was damaged by impacts from the bed of rings, and this damage allowed the flame to penetrate immediately after ignition on a repeat test. It is concluded that the packed bed of rings arrester with a single 30-mesh screen is no more effective than a single 30-mesh screen in withstanding and quenching flashback flames.

SECTION XI

RECOMMENDATIONS

Based upon the results of this test program, the following recommendations are made regarding the selection and installation of flame arresting devices on fuel storage tank vent stacks in a marine environment:

(1) Based upon flame quenching capability, structural durability, and a low susceptibility to corrosion and fouling, the following flame arrester devices have been found effective in preventing flashback flames in an open environment from entering vent openings of a cargo tank containing typical bulk fuels: (1) single 30-mesh stainless-steel screen, (2) dual 20-mesh stainless-steel screen, (3) spiral-wound, crimped stainless steel ribbon, and (4) packed bed of aluminum Ballast rings with single 30-mesh stainless-steel screen retainers. Ethylene, which is a gas at ambient temperature and pressure, is not a typical bulk cargo fuel.

(2) Based upon the ability to withstand 30 minutes of continuous burning of a propane/air mixture, the following flame arrester devices have been found effective in sustaining the flame from typical bulk cargo fuels: (1) single 30-mesh stainless-steel screen, (2) dual 20-mesh stainless-steel screen, (3) spiral-wound, crimped stainless-steel ribbon, and (4) packed bed of Ballast rings with single 30-mesh stainless steel screen retainers. Spiral-wound, crimped metal ribbon arresters appear to have a finite time duration for sustained burning conditions, and should therefore be evaluated for the specific fuel and at the most severe condition of the intended applications. None of the flame arrester devices tested is effective in sustaining the flame from an ethylene/air mixture for 30 minutes duration.

(3) Based upon the inverse relationship between the equilibrium temperature of a screen flame arrester at sustained burning conditions and the fuel/air mixture flowthrough velocity, it is recommended that in fuel transfer operations the rate of fuel flow should be fast enough to keep the exhaust velocity of vented flammable mixture well above the laminar burning velocity of the fuel being transferred. In the event of a flashback flame, this safety precaution will aid in keeping the screen flame arrester on the vent from over-heating by a sustained flame.

(4) The selection of a location for the flame arrester device on the vent stack should be limited to the very end of the pipe. The flame quenching ability of the arrester is reduced by any length of pipe, housing, or mechanical device downstream of the arrester. Screen-type flame arresters are effective only if they are undamaged by punctures or tears in the wire mesh and there are no gaps or holes around the periphery larger than the openings specified for the 20- or 30-mesh screen. All flame arrester devices should be periodically inspected for damage and cleaned to remove fouling and corrosion.

(5) The selection of materials used in the construction of arresters should be based on their compatibility with the local environment and the fuel vapors to be encountered. However, stainless steel is recommended.

The data and experience obtained from these flashback flame and sustained burning tests is limited to those fuel and air mixtures tested in a 15.2-cm-(16-in.-) diameter pipe size. It is recommended that extrapolation of this data should be limited to the following:

(1) Application to other fuels should be limited to those hydrocarbon fuels that have similar combustion characteristics to those fuels tested.

(2) Applications scaled down to pipe sizes smaller than 15.2-cm (6-in.) diameter are considered to be conservative.

(3) Scaled-up applications should be limited to pipe sizes no larger than a 20.3-cm (8-in.) diameter, providing adequate consideration is given to structural strength.

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APPENDIX A

TEST CONFIGURATION LOG

Configuration No.	Test No.	Description
100 to 112	1488 to 1495	The first thirteen test configurations were evolved during the facility checkout tests. They included the preliminary installation of a subscale flame chamber that was later replaced by the full-scale flame chamber and the exhaust collector burn stack. Flame sensors on the flame chamber outer wall were repositioned from the horizontal center line to the top center line. Three igniter positions used in the flame chamber were (1) upstream, (2) middle, and (3) downstream. An aluminum flame shield was installed on the inlet piping upstream of the flame arrester test section. Also, a second aluminum flame shield was installed in front of the downstream flame chamber frangible diaphram. Fuels used on these checkout tests were gasoline and commercial grade propane. The test arresters included both the dual 20-mesh screens and the single 30-mesh screen.
113	1496 (A-C)	This test configuration is shown in Figure 7-2. Flame arrester: dual 20-mesh screens Fuel: propane Igniter position: upstream
114	1497 (A-C)	Flame arrester: dual 20-mesh screens Fuel: propane Igniter position: downstream
115	1498 (A-D)	Flame arrester: single 30-mesh screen Fuel: propane Igniter position: downstream
116	1499 (A-C)	Flame arrester: single 30-mesh screen Fuel: propane Igniter position: upstream
117	1500 (A-C)	Flame arrester: single 30-mesh screen Fuel: ethylene Igniter position: upstream
118	1501 (A)	Changed the exhaust collector burn-stack flame arrester from an Amal spiral-wound, crimped stainless-steel ribbon to a Shand and Jurs spiral-wound, crimped aluminum ribbon assembly. Flame arrester: single 30-mesh screen Fuel: ethylene Igniter position: upstream

Configuration No.	Test No.		Description
119	1501 (B-D)	Flame arrester: Fuel: Igniter position:	single 30-mesh screen ethylene downstream
120	1502 (A)	Flame arrester: Fuel: Igniter position:	none ethylene downstream
121	1502 (B-D)	Flame arrester: Fuel: Igniter position:	dual 20-mesh screens ethylene downstream
122	1503 (A-C)	Flame arrester: Fuel: Igniter position:	dual 20-mesh screens ethylene upstream
123	1504 (A-C)	Flame arrester: Fuel: Igniter position:	crimped ribbon propane upstream

NOTE: All of the following tests were made with the igniter located in the upstream position unless otherwise noted.

124	1505 (A-D)	Flame arrester: Fuel:	crimped ribbon ethylene
125	1506 (A-D)	Flame arrester: Fuel:	crimped ribbon gasoline
126	1507 (A-D)	Flame arrester: Fuel:	none gasoline
127	1507 (C) 1508 (A-B)	Flame arrester: Fuel:	single 30-mesh screen gasoline
128	1508 (C-E)	Flame arrester: Fuel:	dual 20-mesh screens gasoline
129	1509 (A-C)	Flame arrester: Fuel:	packed bed of rings gasoline
130	1510 (A-C)	Flame arrester: Fuel:	packed bed of rings with single 30-mesh screen gasoline

Configuration No.	Test No.	Description	
131	1511 (A-D)	Flame arrester:	packed bed of rings with single 30-mesh screen
		Fuel:	ethylene
132	1512 (A-C)	Flame arrester:	packed bed of rings with single 30-mesh screen
		Fuel:	propane
133	1513 (A-C)	Flame arrester:	single 30-mesh screen
		Fuel:	methyl alcohol
134	1513 (D)	Flame arrester:	none
		Fuel:	methyl alcohol
135	1514 (A-C)	Flame arrester:	dual 20-mesh screens
		Fuel:	methyl alcohol
136	1515 (A-C)	Flame arrester:	dual 20-mesh screens
		Fuel:	toluene
137	1515 (D)	Flame arrester:	none
		Fuel:	toluene
138	1516 (A-D)	Flame arrester:	single 30-mesh screen
		Fuel:	toluene
139	1517 (A-C)	Flame arrester:	single 30-mesh screen
		Fuel:	diethyl ether
140	1517 (D)	Flame arrester:	none
		Fuel:	diethyl ether
141	1518 (A-C)	Flame arrester:	dual 20-mesh screens
		Fuel:	diethyl ether
142	1519 (A-D)	Flame arrester:	dual 20-mesh screens
		Fuel:	butane
143	1519 (E)	Flame arrester:	none
		Fuel:	butane
144	1520 (A-C)	Flame arrester:	single 30-mesh screen
		Fuel:	butane
145	1521 (A-C)	Flame arrester:	single 30-mesh screen
		Fuel:	acetaldehyde

Configuration No.	Test No.	Description	
146	1521 (D)	Flame arrester: Fuel:	none acetaldehyde
147	1522 (A-C)	Flame arrester: Fuel:	dual 20-mesh screens acetaldehyde
148	1523 (A-B)	Changed the test assembly to the sustained burning test configuration. Flame arrester: Fuel:	 crimped ribbon propane
149	1524 (A)	Changed the thermocouples in the test arrester from open tip ungrounded to closed-end grounded. Flame arrester: Fuel:	 crimped ribbon propane
150	1524 (B-C)	Flame arrester: Fuel:	crimped ribbon ethylene
151	1525 (A)	Flame arrester: Fuel:	packed bed of rings with single 30-mesh screen propane
152	1525 (B-C)	Flame arrester: Fuel:	packed bed of rings with single 30-mesh screen ethylene
153	1526 (A)	Flame arrester: Fuel:	15.2-cm- (6.0-in.-) diameter single 30-mesh screen propane
154	1526 (B)	Flame arrester: Fuel:	15.2-cm- (6.0-in.-) diameter dual 20-mesh screens propane
155	1527 (A)	Flame arrester: Fuel:	25.4-cm- (10.0-in.-) diameter single 30-mesh screen propane
156	1527 (B)	Flame arrester: Fuel:	25.4-cm- (10.0-in.-) diameter dual 20-mesh screens propane

APPENDIX B

TABULAR SUMMARY OF STEADY-STATE MEASURED AIR AND FUEL SYSTEM TEST CONDITIONS

LIQUID FUELS

Test No.	Config. No.	PBO, kN/m²	DPO, kN/m²	TO1, °C	PFL, kN/m²	TFL °F	FMF, Hz	PV1, kN/m²	TV1, °C	TV2, °C	TMF, °C	PM1, kN/m²	TM1, °C	T14, °C	TB1, °C	PA1, kN/m²	DPA1, N/m²	DPA2, N/m²	PAMB, kN/m²	VA, m/s	MA, kg/h	MF, kg/h	A/F Ratio	φ E.R.	HCA E.R.
149SE	112	122.96	0.2434	68.6	2119	25.6	178.1	110.7	108.8	257.8	104.8	93.68	47.0	22.6	20.7	93.044	7.0	3.3	93.041	1.573	[illegible]	7.654	[illegible]	1.14	-.77
149A	112	[illegible]	[illegible]	67.5	2158	[illegible]	176.1	111.0	121.8	257.7	151.5	[illegible]	47.3	[illegible]	[illegible]	[illegible]	11.0	11.7	[illegible]	[illegible]	[illegible]	[illegible]	13.75	1.12	0.92
B	112	[illegible]	0.2448	72.2	2210	[illegible]	178.2	111.2	[illegible]	256.5	[illegible]	93.11	48.1	[illegible]	[illegible]	[illegible]	[illegible]	11.0	[illegible]	[illegible]	[illegible]	[illegible]	14.19	1.11	0.71
C	112	126.81	0.2435	72.2	2422	14.3	[illegible]	111.7	127.2	258.3	[illegible]	93.62	[illegible]	54.1	22.4	93.482	7.6	[illegible]	93.476	1.502	[illegible]	7.421	14.03	1.12	[illegible]
147A	114	127.72	0.2224	68.6	2216	13.4	147.6	111.8	125.8	254.8	106.2	93.60	[illegible]	26.2	20.6	93.429	8.2	8.3	[illegible]	1.442	[illegible]	7.507	[illegible]	1.16	[illegible]
B	114	127.14	0.2484	71.1	2241	16.2	173.1	112.1	122.7	[illegible]	106.1	93.48	[illegible]	51.6	22.2	[illegible]	9.7	9.7	[illegible]	1.547	[illegible]	7.571	14.17	1.11	0.71
C	114	126.85	0.2481	71.1	2245	18.1	175.2	111.8	125.2	[illegible]	108.7	93.41	52.1	[illegible]	23.4	93.296	10.2	9.0	[illegible]	1.557	[illegible]	[illegible]	13.78	1.12	[illegible]
148A	115	[illegible]	0.2227	66.6	2210	10.7	162.2	110.6	[illegible]	252.7	105.8	93.45	45.1	22.3	18.1	93.276	[illegible]	6.2	[illegible]	1.447	[illegible]	7.271	14.17	1.11	0.72
B	115	126.20	[illegible]	67.8	1766	16.8	169.8	110.2	124.2	[illegible]	[illegible]	93.23	[illegible]	22.1	24.0	93.076	[illegible]	7.6	[illegible]	1.512	[illegible]	7.442	[illegible]	1.13	0.70
C	115	126.18	0.2358	65.8	2184	17.7	166.4	107.5	121.3	257.6	102.1	93.16	44.2	[illegible]	21.6	[illegible]	6.7	6.7	[illegible]	1.442	[illegible]	[illegible]	14.24	1.10	[illegible]
D	115	126.22	0.2262	67.4	2088	19.7	171.2	101.6	130.0	257.6	[illegible]	93.13	45.7	28.2	22.4	92.965	6.7	6.7	[illegible]	1.481	[illegible]	[illegible]	[illegible]	1.12	0.81
144A	116	126.72	0.2510	74.1	2272	15.7	[illegible]	110.7	121.0	257.4	110.7	93.81	[illegible]	24.6	22.2	93.041	[illegible]	9.0	[illegible]	1.522	[illegible]	7.217	14.72	[illegible]	[illegible]
B	116	121.72	[illegible]	71.3	2121	16.7	164.7	110.7	124.1	259.3	114.1	92.74	[illegible]	[illegible]	[illegible]	[illegible]	8.3	9.0	[illegible]	[illegible]	[illegible]	[illegible]	13.75	1.12	0.77
C	116	126.56	0.2425	72.4	2126	17.9	167.3	[illegible]	123.1	257.7	112.6	93.68	51.8	22.1	24.7	93.224	6.2	6.7	93.217	[illegible]	[illegible]	[illegible]	14.28	1.10	0.87
150-4A	122	128.70	0.2210	58.9	2198	10.3	178.1	111.2	115.7	242.3	72.0	93.85	[illegible]	19.4	15.1	93.751	37.2	37.2	93.717	[illegible]	[illegible]	7.462	[illegible]	[illegible]	0.84
E	122	[illegible]	[illegible]	57.4	2145	11.8	172.2	110.5	127.7	256.8	76.7	93.50	[illegible]	17.9	17.9	[illegible]	[illegible]	37.2	[illegible]	1.443	[illegible]	7.142	[illegible]	[illegible]	0.82
C	122	128.54	0.2220	58.3	2159	11.1	171.4	[illegible]	125.7	[illegible]	75.8	93.59	[illegible]	17.7	12.4	93.476	35.9	35.7	[illegible]	1.432	[illegible]	[illegible]	[illegible]	[illegible]	0.85
156-6A	125	127.68	0.2262	61.1	788.7	3.11	117.5	103.9	202.1	541.3	172.8	93.98	[illegible]	20.3	15.8	93.910	36.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.14	[illegible]
B	125	[illegible]	[illegible]	68.9	770.7	7.8	117.5	106.1	[illegible]	[illegible]	177.7	93.70	[illegible]	[illegible]	28.1	93.654	41.4	42.1	[illegible]	[illegible]	[illegible]	[illegible]	13.24	1.14	[illegible]
C	125	127.81	0.2372	69.2	769.9	11.4	117.8	103.0	208.8	546.4	176.2	93.57	51.3	[illegible]	30.7	[illegible]	42.7	44.1	[illegible]	1.512	[illegible]	[illegible]	13.64	[illegible]	0.70
D	125	127.51	0.2420	71.8	774.0	[illegible]	121.3	105.6	[illegible]	542.7	180.0	93.53	58.4	35.5	27.3	93.467	40.7	42.7	93.427	1.518	[illegible]	[illegible]	[illegible]	1.16	0.70
151-1A	126	127.74	[illegible]	57.7	827.7	15.7	121.7	103.5	188.7	541.9	[illegible]	93.66	40.1	23.1	20.3	[illegible]	2.8	2.8	[illegible]	1.462	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
L	126	127.41	0.2262	59.4	768.4	18.2	118.7	101.7	170.3	537.8	138.8	93.51	41.8	26.1	[illegible]	93.407	3.4	4.1	[illegible]	1.467	[illegible]	[illegible]	12.78	1.14	0.69
C	127	128.01	0.2324	61.8	776.7	15.4	120.1	101.6	209.6	547.3	162.1	93.70	42.9	20.7	12.4	93.579	6.7	7.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.71
154A	127	128.05	0.2448	66.1	782.3	14.7	121.4	103.3	210.3	519.1	172.2	93.85	49.3	26.2	17.1	93.765	6.2	6.7	93.758	1.527	[illegible]	[illegible]	[illegible]	1.12	0.71
L	121	127.82	0.2272	65.4	786.7	14.4	124.5	101.7	214.1	[illegible]	264.4	93.83	48.1	24.8	16.8	93.731	7.6	8.3	93.724	1.480	105.51	8.410	12.54	1.16	0.72
C	128	127.48	0.2265	54.8	784.3	17.8	118.0	102.1	211.3	548.8	149.9	93.69	46.8	26.7	19.2	[illegible]	7.7	9.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.17	0.70
D	123	127.44	0.2234	61.3	786.5	17.3	120.6	103.9	209.3	552.7	138.6	93.62	42.4	27.7	19.6	93.524	7.6	9.0	93.517	1.442	[illegible]	8.101	12.41	1.17	[illegible]
E	125	127.34	0.2372	49.9	787.9	18.3	118.7	101.8	212.1	549.7	145.2	93.60	46.7	28.1	19.7	93.496	2.3	10.2	[illegible]	1.448	[illegible]	8.070	[illegible]	1.16	0.70
155-7A	127	127.94	0.2110	54.8	757.7	10.8	112.6	101.2	248.8	549.8	73.8	93.15	37.0	20.1	15.2	[illegible]	19.3	24.1	93.141	1.511	[illegible]	7.806	12.74	1.15	0.71
L	127	127.22	0.2224	60.2	754.0	12.6	114.5	102.6	207.6	549.2	142.8	93.08	42.4	24.2	17.2	92.934	20.7	24.1	[illegible]	1.444	[illegible]	[illegible]	12.76	1.15	0.70
C	129	127.57	[illegible]	51.8	761.8	10.7	[illegible]	102.8	[illegible]	551.4	136.1	93.06	38.4	21.2	13.0	92.753	22.1	22.9	92.745	1.441	[illegible]	[illegible]	[illegible]	1.17	0.69

LIQUID FUELS (contd)

Test No.	Config. No.	PBO, kN/m²	DPO, kN/m²	TO1, °C	PFL, kN/m²	TFL, °F	FMF, Hz	PV1, kN/m²	TV1, °C	TV2, °C	TMF, °C	PM1, kN/m²	TM1, °C	T14, °C	TB1, °C	PA1, kN/m²	DPA1, N/m²	DPA2, N/m²	PAMB, kN/m²	VA, m/s	MA, kg/h	MF, kg/h	A/F Ratio	φ E.R.	HCA E.R.
1510A	130	127.87	0.2242	65.0	763.5	7.1	114.7	105.0	210.1	345.9	179.2	94.710	48.9	21.7	17.3	93.731	22.8	22.8	94.155	1.419	102.56	7.747	13.90	1.12	0.72
B	130	128.79	0.2331	68.9	768.1	13.6	118.6	104.7	207.3	346.8	169.9	94.53	51.8	29.1	23.1	94.482	24.1	24.8	94.425	1.454	102.28	8.076	12.72	1.15	0.72
C	130	128.37	0.2351	66.8	766.6	14.1	119.8	102.3	205.8	348.3	168.8	94.42	49.1	28.4	21.3	94.372	24.8	25.5	94.344	1.468	105.26	8.160	12.91	1.12	0.71
1512A	132	127.24	0.2192	56.1	2177	12.1	165.3	110.4	123.8	261.1	86.6	92.986	32.8	16.6	12.8	92.876	20.7	20.0	92.255	1.425	102.74	7.376	13.92	1.12	0.71
B	132	127.15	0.2192	56.8	2127	13.4	171.7	110.6	133.2	260.7	97.9	92.896	34.2	18.2	14.1	92.786	20.0	18.6	92.765	1.426	102.20	7.571	13.49	1.16	0.69
C	132	126.86	0.2213	56.6	2129	13.8	167.4	110.1	133.4	258.3	97.8	92.717	34.0	18.2	13.4	92.621	20.0	20.0	92.600	1.430	102.39	7.484	13.68	1.15	0.64
1513A	133	128.67	0.2317	64.2	682.6	7.4	248.4	181.1	168.7	425.1	135.7	93.910	45.2	24.2	16.5	93.800	8.27	7.65	93.773	1.465	104.64	16.27	6.43	1.00	0.67
B	133	128.12	0.2317	66.4	628.0	11.5	243.9	185.2	166.1	423.2	145.4	93.765	50.0	25.8	17.7	93.647	7.58	8.96	93.662	1.448	102.77	16.93	6.15	1.00	0.67
C	133	128.10	0.2310	66.4	606.6	12.7	246.6	187.8	163.2	421.2	143.7	93.758	50.6	28.4	17.2	93.642	6.90	6.18	93.655	1.445	102.56	16.06	6.38	1.01	0.67
D	134	127.72	0.2337	68.6	573.5	14.4	249.2	184.9	159.2	421.7	137.3	N.A.	51.3	27.7	21.5	93.662	3.45	2.76	93.648	1.452	102.15	16.12	6.21	1.02	0.70
1514A	135	127.63	0.2276	65.2	502.7	7.2	252.2	173.2	161.3	423.4	143.7	94.572	56.9	26.3	16.1	94.496	11.0	11.0	94.492	1.445	102.79	16.30	6.29	1.02	0.62
B	135	129.58	0.2324	69.9	472.7	13.4	249.4	181.7	162.1	427.4	140.5	94.177	55.4	31.1	23.1	94.131	12.4	11.7	94.117	1.457	102.11	16.22	[illegible]	1.03	0.70
C	135	128.29	0.2344	70.3	499.9	14.9	253.0	182.3	166.7	427.0	145.1	94.151	56.8	32.8	23.8	94.025	12.4	12.4	94.072	1.462	102.04	16.43	6.21	1.04	[illegible]
1515A	136	128.77	0.2379	67.8	238.5	13.2	75.3	106.9	215.3	343.7	178.7	94.496	52.6	24.5	18.6	94.392	8.96	10.3	94.386	1.452	104.42	7.777	12.09	[illegible]	0.70
B	136	128.50	0.2413	69.7	218.3	14.8	78.7	106.6	214.1	342.7	180.7	94.310	58.1	27.7	22.2	94.234	10.3	10.3	94.220	1.490	105.28	8.163	12.90	1.05	0.70
C	136	127.83	0.2420	74.0	216.1	18.2	76.0	103.7	220.1	343.7	184.0	94.131	55.5	32.1	25.9	94.041	10.3	12.4	94.027	1.428	105.31	7.970	12.77	1.04	0.70
D	137	127.41	0.2402	75.8	220.0	20.7	78.6	104.2	218.0	344.7	181.5	N.A.	61.6	37.4	29.2	93.841	2.76	3.45	93.841	1.527	104.68	8.077	12.91	1.05	0.70
1516A	138	128.03	0.2303	61.4	540.2	11.3	91.3	105.5	193.0	332.3	120.2	93.503	42.7	20.7	15.7	93.421	5.52	6.21	93.420	1.463	104.96	8.217	12.76	1.06	[illegible]
B	138	127.78	0.2331	65.4	444.3	13.9	96.7	101.0	200.7	331.4	128.6	93.400	45.4	24.1	18.8	93.324	6.90	7.58	93.217	1.461	103.47	8.066	12.83	1.05	0.71
C	138	127.14	0.2276	62.1	420.5	14.6	97.2	103.9	174.2	332.7	114.7	93.055	39.1	22.2	19.4	92.979	6.90	7.58	92.972	1.464	103.42	8.077	12.80	1.05	0.67
D	138	127.09	0.2276	61.7	408.7	15.0	96.7	104.9	188.4	334.6	113.3	93.014	37.2	22.8	19.4	92.931	7.58	7.58	92.924	1.470	102.74	8.056	12.09	1.05	0.66
1517A	139	128.83	0.2287	58.3	351.3	2.2	173.6	112.4	159.0	320.8	136.1	93.508	42.9	13.9	10.5	93.430	10.3	12.4	93.427	1.460	106.91	10.80	9.89	1.36	0.70
B	139	128.01	0.2317	61.7	475.2	[illegible]	172.8	110.8	134.4	290.1	128.1	93.345	46.0	19.9	15.5	93.242	7.65	8.96	93.255	1.475	105.78	10.75	9.84	1.14	0.69
C	139	126.89	0.2337	64.4	412.7	7.4	170.6	110.4	136.9	308.4	118.3	93.310	44.4	23.6	21.2	93.255	10.3	11.0	93.218	1.487	104.78	10.56	9.91	1.13	0.69
D	140	127.34	0.2406	66.0	372.0	9.9	175.5	116.4	185.8	277.9	116.7	93.276	47.0	26.4	23.8	93.220	0	0	93.221	1.524	106.55	10.78	9.88	1.13	0.74
1518A	141	127.25	0.2331	[illegible]	693.3	8.1	178.5	108.9	136.2	298.0	113.6	93.510	41.6	15.8	10.1	93.413	6.27	7.58	93.407	1.450	105.92	11.39	9.67	1.16	0.71
B	141	127.88	0.2296	[illegible]	572.7	11.4	176.0	115.8	140.1	300.4	115.5	93.512	42.1	18.8	14.8	93.459	7.58	6.27	93.448	1.450	104.33	10.81	9.65	1.16	0.71
C	141	127.24	0.2441	[illegible]	683.7	14.3	178.1	111.5	127.1	296.6	109.0	93.544	48.7	25.1	17.5	93.462	4.83	4.83	93.455	1.516	107.64	10.92	9.84	1.14	0.72
1519A	142	128.27	0.2213	[illegible]	2119	13.2	138.9	105.6	130.9	261.3	108.7	94.124	40.0	15.8	14.2	94.084	2.76	3.45	94.084	1.298	102.11	7.322	13.93	1.11	0.78
B	142	128.68	0.2321	68.0	2133	14.3	145.4	106.3	137.5	262.2	106.8	94.455	44.6	23.7	19.8	94.379	4.83	5.52	94.343	1.450	102.60	7.584	13.64	1.13	0.75
C	142	128.03	0.2492	69.3	2150	16.1	151.3	107.8	136.8	257.4	115.3	94.282	49.2	29.5	22.6	94.220	5.52	4.83	94.213	1.514	107.19	7.816	13.70	1.13	0.75
D	143	127.81	0.2441	[illegible]	2141	12.6	147.2	105.6	141.1	261.1	120.2	94.241	48.7	27.7	25.3	94.164	6.21	6.89	94.179	1.504	106.23	7.598	13.91	1.11	0.75

LIQUID FUELS (contd)

Test No.	Config. No.	PBO, kN/m^2	DPO, kN/m^2	TO1, °C	PFL, kN/m^2	TFL °F	FMF, Hz	PV1, kN/m^2	TV1, °C	TV2, °C	TMF, °C	PM1, kN/m^2	TM1, °C	T14, °C	T81, °C	PA1, kN/m^2	DPA1, N/m^2	DPA2, N/m^2	PAMB, kN/m^2	VA, m/s	MA, kg/h	MF, kg/h	A/F Ratio	ϕ E.R.	HCA E.R.
1519E	143	127.56	2448	[illegible]	2121	[illegible]	151.2	104.9	158.5	267.2	115.1	74.226	51.3	52.4	29.2	74.161	2.07	2.07	74.151	1.515	104.92	7.734	13.57	1.14	0.79
1520A	144	[illegible]	2358	63.9	2123	15.8	152.1	105.7	131.8	257.2	[illegible]	73.144	57.9	21.0	17.8	73.128	6.94	6.21	73.131	1.462	[illegible]	[illegible]	13.43	1.15	0.80
B	144	127.59	2255	57.5	2219	15.6	148.1	[illegible]	132.2	261.2	[illegible]	73.401	[illegible]	21.7	17.7	73.392	7.58	8.76	73.396	1.418	104.40	7.707	13.57	1.14	0.80
C	144	[illegible]	2241	56.4	2174	15.9	148.5	108.2	130.2	254.2	102.0	73.633	[illegible]	17.7	16.4	73.627	7.58	8.27	73.620	1.409	104.69	7.702	13.59	1.14	0.79
1521A	145	129.37	2321	66.7	377.9	11.7	203.9	147.5	123.1	[illegible]	121.8	74.436	42.1	20.2	15.6	74.441	11.72	12.41	74.427	[illegible]	101.22	14.82	6.83	1.16	0.63
B	145	128.78	2327	68.1	480.5	13.2	201.4	139.9	156.2	250.2	[illegible]	74.427	51.8	26.1	[illegible]	74.427	12.41	13.10	74.413	1.458	[illegible]	14.74	6.95	1.13	0.64
C	145	[illegible]	2462	68.7	424.4	15.5	214.0	142.5	149.4	[illegible]	124.3	74.128	51.4	27.2	22.6	74.131	13.10	13.10	74.117	1.558	108.14	[illegible]	6.90	1.14	0.62
D	146	127.90	2434	71.9	501.5	12.8	210.9	149.3	150.4	[illegible]	125.4	74.022	[illegible]	34.1	26.2	74.020	7.58	8.76	74.013	1.557	104.60	[illegible]	6.83	1.15	0.60
1522A	147	128.75	2302	66.5	1124	14.5	209.6	141.5	125.9	[illegible]	114.6	74.246	45.6	[illegible]	17.4	74.241	6.89	8.27	74.224	1.422	102.56	[illegible]	6.77	1.17	0.59
B	147	127.87	2310	70.3	1161	17.0	206.5	141.2	125.1	[illegible]	116.1	73.989	50.6	29.1	[illegible]	73.984	7.58	6.89	73.979	1.422	[illegible]	[illegible]	6.82	1.15	0.66
C	147	127.91	2321	67.6	1156	17.5	208.8	141.1	130.2	[illegible]	114.7	73.911	[illegible]	29.2	21.8	73.910	7.58	7.58	73.912	1.452	101.47	[illegible]	6.83	1.15	0.66
1523A	148	127.85	2262	68.6	2154	15.6	175.8	107.3	137.2	241.4	114.9	73.462	41.4	[illegible]	15.1	73.429	44.12	48.26	73.448	1.412	101.20	7.480	13.52	1.16	0.99
B	148	127.12	2406	67.3	2120	18.6	158.9	102.7	132.7	249.3	100.9	73.294	[illegible]	27.7	[illegible]	73.277	48.27	49.64	73.249	1.477	[illegible]	7.021	15.02	1.04	1.00
1524A	149	127.98	2272	69.1	2137	15.2	166.5	108.5	142.0	[illegible]	110.2	73.710	[illegible]	21.6	17.6	73.728	45.21	46.20	73.696	1.453	104.10	7.327	14.14	1.11	1.04
1525A	151	124.76	2358	68.9	2142	23.4	170.9	108.8	99.8	[illegible]	[illegible]	[illegible]	27.0	26.4	[illegible]	73.813	6.21	6.21	73.806	1.464	[illegible]	[illegible]	14.01	1.12	1.00
1526A	153	127.00	2413	73.4	2171	21.8	172.4	107.9	102.7	200.7	84.7	73.542	[illegible]	24.2	24.1	73.558	6.21	6.21	73.551	1.458	102.46	7.430	13.81	1.14	0.97
B	154	126.31	2476	77.4	2137	25.1	170.5	107.7	107.4	[illegible]	95.9	73.456	[illegible]	21.4	30.9	73.413	7.58	8.27	73.407	1.506	[illegible]	7.285	14.18	1.10	0.94
1527A	155	126.92	2482	76.8	2186	24.3	177.3	110.1	75.4	206.4	95.2	73.830	45.1	29.6	26.6	73.813	3.45	4.14	73.806	1.491	105.27	7.562	13.23	1.14	1.01
B	156	125.97	2606	80.7	2160	29.5	182.7	110.1	111.6	[illegible]	97.8	73.569	[illegible]	41.1	27.9	[illegible]	6.21	6.89	[illegible]	1.527	[illegible]	7.642	13.89	1.13	1.00

GASEOUS FUELS

Test No.	Config. No.	PBO, kN/m²	DPO, kN/m²	TO1, °C	PGF, kN/m²	TGF, °C	DPG, kN/m²	PV1, kN/m²	TV1, °C	TV2, °C	TMF, °C	PM1, kN/m²	TM1, °C	T14, °C	TB1, °C	PA1, kN/m²	DPA1, N/m²	DPA2, N/m²	PAMB, kN/m²	VA, m/s	MA, kg/h	MFG, kg/h	A/FG Ratio	φ E.R.	HCA E.R.
1500A	117	129.75	0.2296	63.8	522.9	14.7	222.1	125.5	130.1	192.3	109.9	94.79	42.6	15.8	15.6	94.633	7.6	8.3	94.627	1.437	104.69	8.119	12.89	1.15	0.79
B	117	128.51	0.2344	67.4	518.5	16.9	222.0	123.3	107.7	191.4	85.6	94.79	45.9	27.7	22.7	94.441	9.0	8.3	94.454	1.457	103.06	7.923	12.91	1.15	0.71
C	117	128.81	0.2338	69.7	526.0	18.7	225.1	[illegible]	132.1	206.9	111.3	94.49	46.4	27.2	25.4	94.308	8.3	8.3	94.301	1.472	102.69	[illegible]	13.69	1.16	0.71
1501A	118	127.38	[illegible]	66.7	510.6	15.7	214.6	123.6	128.6	197.1	108.8	94.55	42.5	20.1	17.4	94.330	11.0	12.4	94.317	1.420	102.61	7.847	13.06	1.14	0.69
B	119	128.16	0.2394	68.7	527.4	17.5	225.8	124.6	122.1	200.4	99.7	94.41	42.6	25.7	24.1	94.227	11.0	11.0	94.213	1.447	105.76	8.165	12.98	1.14	0.77
C	119	128.74	0.2413	71.7	522.2	18.2	222.0	124.6	128.1	177.1	110.6	94.41	49.3	30.2	27.3	94.220	10.3	11.0	94.206	[illegible]	104.76	[illegible]	13.05	1.14	0.70
D	119	128.21	0.2420	73.8	531.3	20.0	229.8	[illegible]	129.2	198.7	110.8	94.38	49.6	31.0	25.6	94.199	11.7	11.7	94.184	[illegible]	[illegible]	8.210	12.68	1.17	0.70
1502A	120	128.47	0.2434	70.4	538.2	18.3	232.2	124.8	131.6	204.0	111.8	94.24	49.2	26.4	25.3	[illegible]	6.9	6.7	94.012	1.400	106.65	8.346	12.70	1.16	0.68
B	121	[illegible]	0.2448	74.7	523.2	20.1	222.3	123.2	131.9	203.0	112.2	94.03	49.9	33.4	27.7	93.896	9.7	10.3	93.859	1.500	[illegible]	8.094	12.86	1.15	0.68
C	121	127.27	0.2413	70.4	527.9	20.1	228.2	122.0	112.4	180.3	71.8	93.131	46.1	31.4	26.1	93.813	10.3	9.7	[illegible]	1.498	104.06	8.117	12.82	1.15	0.69
D	121	127.19	0.2286	72.9	524.1	20.8	224.0	121.5	125.3	205.9	98.4	93.292	45.4	30.4	24.9	93.788	9.0	9.0	[illegible]	1.437	[illegible]	8.059	12.72	1.16	0.68
1503A	122	[illegible]	0.2365	64.7	[illegible]	13.8	207.5	120.8	131.1	206.1	107.3	93.475	42.8	17.1	14.7	93.482	8.3	7.7	93.476	1.423	[illegible]	7.666	13.42	1.11	0.67
B	122	127.61	0.2379	67.6	515.8	18.1	220.2	123.5	131.2	203.4	114.9	93.613	44.3	21.8	20.7	93.407	10.3	11.0	93.393	1.422	[illegible]	7.738	12.72	1.16	0.66
C	122	126.85	0.2411	73.7	515.3	19.2	221.2	121.1	115.4	191.6	94.8	93.503	45.6	31.6	29.6	93.296	10.3	11.7	93.282	1.456	99.97	[illegible]	12.69	1.17	0.66
1505A	124	130.47	0.2255	61.0	519.9	[illegible]	217.0	124.4	129.7	203.2	110.7	94.510	43.3	18.7	13.4	94.455	35.9	36.5	[illegible]	1.440	105.10	[illegible]	13.02	1.14	0.73
B	124	129.98	0.2241	63.1	505.8	14.3	210.4	122.8	130.0	203.6	110.3	94.386	42.7	19.6	18.7	94.317	[illegible]	38.6	94.292	1.404	102.51	[illegible]	13.14	1.13	0.71
C	124	129.05	0.2334	67.0	503.8	16.5	211.5	122.4	127.2	202.3	107.4	94.234	42.3	[illegible]	21.5	94.165	38.6	40.0	[illegible]	1.454	[illegible]	7.711	13.47	1.10	0.71
D	124	128.70	0.2331	67.1	506.7	15.4	213.2	123.0	120.9	203.8	111.7	94.144	46.4	26.9	22.6	[illegible]	38.6	40.0	[illegible]	1.456	102.74	[illegible]	13.16	1.12	0.72
1511A	131	127.76	0.2282	63.4	507.4	12.7	213.2	121.9	126.1	205.1	104.1	93.124	42.8	15.7	12.7	[illegible]	24.8	20.7	[illegible]	1.421	[illegible]	7.847	13.41	1.13	0.73
B	131	127.43	0.2303	66.4	521.8	16.2	224.9	124.8	132.2	201.4	110.8	93.062	44.7	21.2	18.9	92.986	20.7	20.0	92.965	1.456	101.79	8.074	12.61	1.18	0.74
C	131	126.87	0.2344	69.1	519.8	16.6	223.3	124.1	133.4	206.5	112.1	[illegible]	37.8	26.1	21.8	92.841	22.1	22.8	92.820	1.451	101.33	8.074	12.55	1.18	0.76
D	131	126.52	0.2482	70.4	524.9	16.1	232.8	121.9	74.8	112.7	65.3	92.793	44.8	28.6	20.9	92.710	21.4	23.5	[illegible]	1.536	106.87	8.165	13.09	1.13	0.73
1524B	150	126.85	0.2474	71.2	507.2	21.4	186.0	122.4	143.7	202.7	105.6	93.572	48.6	31.9	22.7	93.441	27.23	28.41	93.407	1.578	104.51	[illegible]	13.50	1.13	0.95
C	150	126.67	0.2413	70.4	505.3	22.3	198.7	119.8	144.2	199.8	108.3	93.503	47.8	30.9	25.2	[illegible]	37.92	[illegible]	93.358	1.570	102.60	[illegible]	13.45	1.10	0.97
1525B	152	126.54	0.2448	68.4	523.4	24.0	208.0	111.0	129.1	192.6	99.3	93.386	43.7	30.6	25.9	[illegible]	21.38	24.13	93.310	1.614	106.37	7.983	13.32	1.11	0.84
C	152	126.45	0.2425	70.5	518.2	25.5	198.4	111.0	136.7	198.7	98.5	93.310	44.6	32.7	24.2	[illegible]	20.69	22.75	93.241	1.610	106.01	[illegible]	13.41	1.10	0.83

APPENDIX C

TABULAR SUMMARY OF TRANSIENT-STATE MEASURED FLAME SPEED AND PEAK PRESSURE RISE

		Flame Chamber Test Data														Inlet Piping Test Data									
		Peak Pressure Rise				Flame Sensor Flame Speeds						Photographic Flame Speeds				Peak Pressure Rise					Flame Sensor Flame Speeds				
Test No.	Config. No.	DP81, N/m^2	DP83, N/m^2	DP85, N/m^2	DP87, N/m^2	F81-F82, m/s	F82-F83, m/s	F83-F84, m/s	F84-F85, m/s	F85-F88, m/s	F86-F87, m/s	SA-S1, m/s	S1-S2, m/s	S2-S3, m/s	S3-S4, m/s	P73, kN/m^2	P72, kN/m^2	P71, kN/m^2	P21, kN/m^2	P12, kN/m^2	F81-F73, m/s	F73-F72, m/s	F72-F71, m/s	F71-F21, m/s	F21-F12, m/s
1495E	112	746	726	744	804	2.04	6.02	2.72	5.89	8.91	N.A.[a]	N.A.	N.A.	N.A.	N.A.	851.3	265.4	191.0	361.8	217.6	2.32	2.35	2.41	7.03	18.94
1496A	113	1053	1048	920	992	4.96	7.01	9.68	10.51	2.09	8.24	N.A.	N.A.	N.A.	N.A.										
B	113	972	718	797	706	5.54	7.62	10.70	15.24	10.85	12.42	2.15	3.39	2.97	3.11										
C	113	769	834	838	745	5.54	7.53	8.21	7.17	4.23	5.64	2.21	3.11	2.97	4.15										
1497A	114	989	1085	955	1031	2.28	2.00	2.05	1.91	1.77	3.60	2.45	1.79	1.56	1.40										
B	114	825	888	838	821	3.00	2.90	2.19	2.09	2.38	3.67	2.64	5.08	2.15	1.78										
C	114	618	789	878	840	4.32	3.45	3.72	4.72	4.92	3.98	3.84	7.36	2.97	2.49										
1498A	115	810	834	883	802	2.82	2.81	2.56	3.11	4.38	4.23	5.11	2.39	1.98	1.66										
B	115	729	737	639	725	2.67	2.00	3.09	4.06	4.29	5.59	2.84	2.54	2.79	2.79										
C	115	810	718	675	725	2.77	1.81	1.68	2.08	1.40	4.26	3.27	1.91	1.29	1.31										
D	115	729	756	752	783	3.06	2.83	2.51	3.91	2.68	3.81	3.49	2.54	1.98	2.08										
1499A	116	830	854	846	783	5.08	7.01	8.59	12.19	13.33	11.72	3.95	4.93	9.54	6.22										
B	116	891	912	876	783	4.92	6.77	7.26	13.55	15.64	16.47	2.95	4.93	9.54	4.98										
C	116	891	892	883	859	5.21	7.26	7.82	13.54	18.02	21.02	4.33	6.10	9.54	6.22										
1500A	117	NO	IGN	ITIO	N																				
B	117	1060	1099	1028	980	5.25	8.16	7.43	9.38	5.64	12.19	4.78	7.62	5.94	6.22										
C	117	1035	1122	960	980	5.28	7.87	8.71	17.62	6.78	15.45	4.78	6.10	5.94	8.30										
1501A	118	1013	965	914	763	5.56	7.39	7.97	9.18	6.45	13.77	3.95	4.36	4.95	4.98										
B	119	966	987	1005	938	3.54	3.40	2.64	8.56	3.06	6.21	3.78	2.77	2.29	2.26										
C	119	848	898	845	785	3.66	3.77	3.78	2.74	2.83	7.32	4.78	3.39	2.70	2.08										
D	119	895	920	914	872	2.23	2.89	2.31	2.46	2.69	9.39	4.54	3.39	2.47	1.18										
1502A	120	1251	1571	1671	1483	10.84	10.84	9.95	7.78	7.50	11.24	8.83	3.05	7.43	6.22	336.5	178.5	304.4	>440	>440	2.90	6.93	8.47	22.53	>1800
B	121	769	763	747	698	3.63	3.74	3.11	2.47	1.51	5.44	4.65	3.81	4.25	3.56										
C	121	794	740	682	698	2.31	4.08	3.06	2.57	0.94	4.08	2.39	5.08	1.35	1.81										
D	121	818	808	858	872	4.67	3.76	2.85	2.37	2.00	5.19	5.19	3.81	3.31	2.08										
1503A	122	1342	1442	1234	1158	5.38	7.57	9.20	7.11	20.61	12.20	5.19	5.08	7.43	8.30	147.0	246.7	285.8	>440	>440	3.68	8.30	4.33	18.68	>1800
B	122	1201	1099	1120	1010	6.29	9.34	11.28	9.49	11.28	15.23	6.29	7.62	7.43	8.30	150.6	252.0	278.2	>440	>440	3.37	7.36	5.92	15.76	>1800
C	122	1036	1053	1005	1158	4.86	7.66	7.72	7.03	10.97	8.92	4.90	6.10	7.43	8.30	146.9	147.3	256.7	>440	>440	4.28	5.34	3.69	15.47	>1800
1504A	123	1319	1418	1325	1223	3.89	4.71	6.55	6.77	6.15	7.53	3.40	3.81	4.35	4.98										
B	123	1439	1442	1417	1414	4.30	5.29	9.56	10.95	11.37	12.55	3.82	4.72	5.94	8.30										
C	123	1413	1396	1393	1265	4.91	6.15	8.22	10.49	16.01	16.90	4.38	5.08	8.68	6.22										
1505A	124	1389	1526	1531	1396	8.52	8.49	8.76	13.93	16.58	32.24	3.32	2.54	4.45	4.98										

[a]N.A. - Not available.

		Flame Chamber Test Data														Inlet Piping Test Data									
		Peak Pressure Rise				Flame Sensor Flame Speeds						Photographic Flame Speeds				Peak Pressure Rise					Flame Sensor Flame Speeds				
Test No.	Config. No.	DP81, N/m^2	DP83, N/m^2	DP85, N/m^2	DP87, N/m^2	F81-F82, m/s	F82-F83, m/s	F83-F84, m/s	F84-F85, m/s	F85-F86, m/s	F86-F87, m/s	SA-S1, m/s	S1-S2, m/s	S2-S3, m/s	S3-S4, m/s	P73, kN/m^2	P72, kN/m^2	P71, kN/m^2	P21, kN/m^2	P12, kN/m^2	F81-F73, m/s	F73-F72, m/s	F72-F71, m/s	F71-F21, m/s	F21-F12, m/s
1505B	124	1131	1055	1097	1243	7.38	6.95	7.20	7.81	7.75	19.36	3.41	2.34	5.94	4.78										
C	124	1319	1369	1417	1221	6.24	6.88	7.88	11.74	12.74	15.36	7.83	7.39	4.95	7.98										
D	124	1578	1504	1599	1504	6.45	9.01	13.47	15.54	30.30	22.44	6.13	6.10	7.47	12.44										
1506A	125	707	718	731	824	2.67	3.61	1.21	2.36	1.63	2.07	N.A.[a]	N.A.	N.A.	N.A.										
B	125	757	845	845	975	2.83	3.19	1.44	2.30	1.38	3.56														
C	125	942	1032	1097	1113	3.57	4.19	3.97	2.73	1.77	3.72														
D	125	707	809	913	1069	6.38	6.31	2.87	3.92	2.32	2.27														
1507A	126	NO	IG	NIT	ION																				
B	126	1198	1036	1043	972	6.48	4.46	2.32	N.A.	N.A.	N.A.					183.2	187.6	155.3	109.7	93.8	2.00	4.12	3.46	4.96	[illegible]
C	127	784	907	981	971	4.02	6.82	7.23	5.16	4.97	3.51														
1508A	127	958	994	1005	930	3.49	6.58	2.97	1.60	0.84	0.64														
B	127	1045	1036	1045	1069	3.69	6.70	7.82	5.43	3.11	3.67														
C	128	914	994	965	1148	3.83	7.56	6.13	3.76	1.25	2.04														
	128	1176	1318	1125	1148	4.40	8.67	5.06	4.78	3.07	3.57														
	128	1350	1274	1429	1227	4.61	8.01	9.64	3.61	3.72	4.35	N.A.	N.A.	N.A.	N.A.										
1509A	129	1595	1569	1647	1527	2.64	3.36	16.34	25.86	42.79	54.01	2.72	N.A.	3.72	3.26	384.4	139.7	300.6	>440	>440	3.63	1.21	6.14	4.20	2.00
B	129	1091	1060	1045	916	2.95	3.21	18.15	30.45	72.11	88.15	2.35	3.05	3.30	4.38	346.6	211.5	292.4	>440	>470	3.43	6.82	1.21	4.82	2.02
C	129	1595	1526	1507	1317	4.57	5.49	25.15	24.14	35.51	64.35	N.A.	N.A.	4.95	4.98	368.6	152.5	265.3	>470	>470	2.98	1.59	3.12	3.96	2.06
1510A	130	871	858	864	894	2.86	2.41	2.10	2.55	2.60	2.18	1.65	2.03	N.A.	N.A.										
B	130	1089	1101	1205	1282	5.06	9.13	8.25	2.54	2.00	3.65	2.47	3.39	4.25	2.76										
C	130	1132	1034	1226	1263	5.14	6.43	9.49	2.74	2.47	2.69	2.72	4.35	3.30	N.A.										
1511A	131	666	715	733	719	5.24	5.24	6.99	9.83	12.98	17.47	3.98	3.39	5.94	2.76										
B	131	666	787	708	874	7.59	5.91	5.63	8.07	12.80	14.63	4.71	4.36	5.94	4.98										
C	131	745	930	960	777	8.60	8.03	8.86	10.38	11.27	12.29	5.75	6.10	5.94	8.30										
D	131	1243	1168	1234	1166	5.23	8.82	9.84	12.64	17.65	16.79	5.25	6.16	7.43	12.44	365.7	208.5	285.7	276.1	227.7	3.12	6.98	8.44	22.03	>180
1512A	132	740	858	868	874	4.35	4.71	2.67	2.86	5.41	N.A.	3.04	3.81	3.72	1.91										
B	132	1307	1454	1280	1127	4.61	5.62	5.57	7.36	9.66	9.51	3.23	4.36	4.95	4.98										
C	132	1067	954	1090	1088	5.35	5.75	5.09	3.22	11.71	9.27	2.04	4.36	5.94	4.15										
1513A	133	980	937	941	933	3.36	6.22	4.68	2.94	N.A.	N.A.	3.49	4.36	4.95	6.22										
B	133	784	721	762	933	3.50	4.55	3.93	2.34	N.A.	N.A.	2.52	3.81	3.72	8.56										
C	133	691	721	784	777	3.16	4.69	2.83	1.34	N.A.	N.A.	2.67	3.81	4.25	4.15										
D	134	784	841	852	1010	4.46	6.63	5.07	4.09	N.A.	N.A.	3.28	4.36	5.94	4.98	186.4	134.5	176.0	322.2	300.1	2.19	2.78	3.80	[illegible]	N.A.

[a]N.A. - Not available.

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		Flame Chamber Test Data														Inlet Piping Test Data									
		Peak Pressure Rise				Flame Sensor Flame Speeds						Photographic Flame Speeds				Peak Pressure Rise					Flame Sensor Flame Speeds				
Test No.	Config. No.	DPB1, N/m^2	DPB3, N/m^2	DPB5, N/m^2	DPB7, N/m^2	FB1-FB2, m/s	FB2-FB3, m/s	FB3-FB4, m/s	FB4-FB5, m/s	FB5-FB6, m/s	FB6-FB7, m/s	SA-S1, m/s	S1-S2, m/s	S2-S3, m/s	S3-S4, m/s	P73, kN/m^2	P72, kN/m^2	P71, kN/m^2	P21, kN/m^2	P12, kN/m^2	FB1-F73, m/s	F73-F72, m/s	F72-F71, m/s	F71-F21, m/s	F21-F12, m/s
1514A	135	871	828	792	777	3.74	4.95	4.65	4.38	N.A.[a]	N.A.	2.76	3.81	4.09	4.98										
B	135	871	828	858	855	4.74	5.68	4.40	3.45	N.A.	N.A.	3.53	6.10	4.95	3.56										
C	135	741	828	703	758	5.47	5.89	6.06	4.50	N.A.	N.A.	3.53	6.10	4.95	4.98										
1515A	136	741	731	740	699	4.61	5.08	6.25	2.72	3.66	2.37	2.29	2.77	3.30	3.56										
B	136	805	852	876	952	5.64	6.15	6.63	2.92	4.23	2.71	3.15	4.36	4.95	4.98										
C	136	479	584	583	679	6.55	7.00	7.00	4.94	4.13	4.71	3.68	6.10	4.95	4.98										
D	137	762	706	762	1010	7.89	8.00	9.57	4.03	9.00	3.37	4.90	6.10	4.95	9.70	207	155	121	N.A.	N.A.	7.61	7.43	3.72	N.A.	N.A.
1516A	138	697	654	650	661	3.32	7.00	3.92	1.50	0.61	1.29	1.89	1.45	1.98	3.56										
B	138	522	514	493	505	4.89	6.72	5.91	2.82	4.15	2.12	3.02	4.36	3.72	4.15										
C	138	566	561	605	622	4.96	6.23	5.69	2.60	4.80	2.22	3.13	3.39	4.25	3.11										
D	138	595	561	583	641	5.49	6.83	5.64	3.10	3.70	7.42	3.49	4.36	3.72	2.76										
1517A	139	741	779	740	672	5.77	5.08	6.38	12.50	9.23	N.A.	2.93	2.54	3.72	4.15										
B	139	1116	1071	896	816	5.12	5.40	9.00	12.04	4.84	N.A.	3.49	3.05	4.25	4.98										
C	139	946	974	941	1069	6.29	6.14	8.89	10.93	9.11	N.A.	4.33	5.08	4.95	6.22										
D	140	610	633	695	672	7.60	8.11	8.57	15.79	10.91	N.A.	5.04	6.10	7.43	8.30	257	166	141	773	497	2.98	3.61	4.01	4.95	17.43
1518A	141	1157	1407	1348	1224	4.89	6.01	4.42	7.50	N.A.	N.A.	3.68	2.81	5.94	6.22										
B	141	840	811	914	874	4.16	5.94	4.34	N.A.	N.A.	N.A.	2.94	3.05	4.95	4.15										
C	141	840	1169	1211	1166	5.36	6.25	5.08	N.A.	N.A.	N.A.	3.68	5.08	4.95	4.98										
1519A	142	962	925	960	948	2.25	4.96	3.23	2.75	1.63	2.83	1.96	2.03	2.29	N.A.										
B	142	876	901	1028	1028	4.25	5.54	2.72	2.99	1.61	2.31	2.39	2.34	2.48	3.56										
C	142	876	925	914	968	2.40	5.25	4.68	4.61	4.25	3.24	3.15	5.08	3.72	3.56										
D	142	940	1047	960	1028	2.98	5.29	6.22	5.80	4.49	4.60	3.34	4.36	4.25	4.15										
E	143	798	755	845	968	4.17	6.67	4.84	3.63	2.86	4.58	4.41	5.08	4.95	6.22	209	158	113	290	N.A.	2.26	3.15	5.27	3.55	13.58
1520A	144	945	901	937	877	2.52	3.15	2.88	2.04	0.44	1.78	2.39	2.03	3.72	2.76										
B	144	840	877	868	907	3.12	4.67	2.91	0.34	1.70	1.87	2.39	4.36	2.97	2.76										
C	144	965	934	935	1028	3.90	5.10	2.29	2.64	0.59	0.49	2.67	3.39	3.30	3.56										
1521A	145	1069	1025	1074	968	4.47	5.32	7.59	9.64	6.75	13.20	3.95	3.81	7.95	6.22										
B	145	534	572	578	565	4.38	5.36	5.88	7.29	5.77	4.71	3.78	4.36	4.95	4.98										
C	145	1133	1359	1280	1452	5.34	7.36	274	11.61	17.87	21.56	5.67	6.10	7.73	8.30										
D	146	1005	1097	1280	1371	4.93	7.33	6.39	8.35	10.71	15.41	4.33	6.10	5.97	6.22	319	187	237	[illegible]	N.A.	3.22	[illegible]	[illegible]	[illegible]	[illegible]
1522A	147	1176	1267	1051	1049	5.43	6.21	6.98	8.37	5.69	7.35	4.01	5.28	4.95	6.22										
B	147	1176	1389	1302	1462	6.61	9.81	8.35	10.55	13.85	16.70	5.52	6.10	5.94	8.30										
C	147	1259	1242	1142	1029	5.92	7.45	7.24	10.23	8.05	6.16	5.19	6.10	7.43	8.30										

[a]N.A. - Not available.

APPENDIX D

TABULAR SUMMARY OF AVERAGED MEASURED FLAME SPEED AND PEAK PRESSURE RISE FOR FUELS

Fuel Type	Flame Chamber Test Data: Peak Pressure Rise				Flame Sensor Flame Speed						Photographic Flame Speed			
	DPB1, N/m^2	DPB3, N/m^2	DPB5, N/m^2	DPB7, N/m^2	FB1-FB2, m/s	FB2-FB3, m/s	FB3-FB4, m/s	FB4-FB5, m/s	FB5-FB6, m/s	FB6-FB7, m/s	SA-S1, m/s	S1-S2, m/s	S2-S3, m/s	S3-S4, m/s
PROPANE[a]	1139	1039	1019	974	4.75	6.27	7.21	9.74	10.65	13.63	3.40	4.42	6.19	5.02
PROPANE[b]	782	530	802	818	2.99	2.66	2.54	3.13	2.12	4.16	3.38	2.02	2.02	1.39
ETHYLENE[a]	1101	1131	1110	1067	6.60	7.63	8.64	10.41	13.27	16.27	4.75	4.76	5.87	6.85
ETHYLENE[b]	906	955	960	904	4.35	4.98	4.70	4.12	3.33	7.83	4.02	3.61	3.40	3.34
GASOLINE	973	997	1033	1068	4.22	6.41	5.04	3.34	2.38	2.42	2.42	3.21	3.98	3.92
METHANOL	818	824	812	863	4.35	5.52	4.66	3.28	N.A.	N.A.	3.18	4.62	4.69	4.63
TOLUENE	640	645	661	724	5.42	6.27	6.14	3.08	4.28	2.65	3.21	4.11	3.98	4.43
DIETHYL ETHER	892	978	964	913	5.61	6.06	6.67	11.95	9.77	N.A.	3.73	4.10	5.17	5.53
BUTANE	894	913	920	965	3.62	5.07	3.72	3.10	2.29	2.71	2.90	3.58	3.46	3.50
ACETALDEHYDE	1050	1135	1096	1128	5.30	6.98	7.23	9.50	9.81	12.11	4.64	5.38	5.94	6.93

Fuel Type	Inlet Piping Test Data: Peak Pressure Rise					Flame Sensor Flame Speed				
	P73, kN/m^2	P72, kN/m^2	P71, kN/m^2	P21, kN/m^2	P12, kN/m^2	FB1-F73, m/s	F73-F72, m/s	F72-F71, m/s	F71-F21, m/s	F21-F12, m/s
PROPANE[a]	855	265	181	348	218	2.32	2.35	2.41	2.03	18.94
PROPANE[b]	—	—	—					—		
ETHYLENE[a]	174	215	274	>440	>440	3.91	3.00	11.65	16.52	>180
ETHYLENE[b]	337	179	204	>440	>440	4.90	6.43	8.47	22.53	>180
GASOLINE	183	190	155	110	94	2.00	4.12	4.16	4.69	5.49
METHANOL	186	135	126	322	300	2.19	2.98	3.30	9.15	N.A.
TOLUENE	207	155	121	N.A.	N.A.	3.61	4.43	3.32	N.A.	N.A.
DIETHYL ETHER	247	166	101	483	493	2.98	7.41	4.01	4.85	14.93
BUTANE	204	158	113	290	N.A.	3.26	3.35	5.27	7.55	12.54
ACETALDEHYDE	319	187	237	400	N.A.	3.22	4.07	6.44	8.76	40.5

[a]Igniter position upstream.

[b]Igniter position downstream.

APPENDIX E

TABULAR SUMMARY OF TEMPERATURE MEASUREMENTS FOR SUSTAINED BURNING TESTS

Test No.	Config. No.	Time, s	TBA, °C	TBB, °C	TBC, °C	TBD, °C	TBE, °C	TBF, °C
1524A	149	0	21.4	19.2	19.9	18.8	18.1	22.2
		120	27.2	19.9	20.2	48.5	18.8	21.1
		240	47.7	20.4	20.5	92.5	19.4	22.4
		360	55.6	21.1	20.7	144.4	20.2	24.0
		480	58.1	20.4	20.6	232.1	19.3	22.4
		600	60.1	21.0	21.0	474.5	20.1	22.7
		720	61.1	21.7	21.4	755.9	20.7	24.7
		840	62.0	22.5	22.0	967.8	21.2	25.3
		960	63.0	24.2	22.8	972.8	21.6	26.3
		1080	61.8	27.0	22.6	975.7	20.5	25.2
		1200	60.7	37.5	24.9	972.9	22.0	25.9
		1320	60.3	64.0	27.0	972.2	25.0	26.6
		1440	57.5	102.9	35.6	954.2	30.7	27.4
		1560	60.4	172.3	45.5	947.2	42.9	27.7
		1680	106.3	300.7	57.2	928.5	67.2	27.0
		1800	298.5	529.6	83.6	954.4	137.7	26.6
		1860	270.6	579.2	106.5	935.4	175.3	26.9
		1920	152.6	580.6	136.5	915.7	210.1	27.3
1524B	150	0	27.3	26.9	27.1	27.1	26.1	30.0
		60	106.0	27.3	27.3	70.3	26.3	30.1
		90	517.0	27.4	27.4	513.5	26.4	30.1
		120	847.3	27.4	27.2	840.5	26.5	30.2
		150	955.4	27.9	27.4	880.3	26.9	30.3
		180	921.2	27.7	27.6	878.4	27.9	30.4
		210	923.7	55.7	27.0	912.7	37.4	27.9
		240	954.6	225.6	26.8	915.1	78.0	29.7
		270	957.0	812.2	26.7	917.0	714.3	29.7
		300	940.6	943.0	26.9	919.7	878.9	29.8
		330	1006.8	880.0	28.1	897.2	889.0	30.3
		360	1016.0	876.3	31.4	878.6	874.7	31.9
		390	1025.0	882.0	55.9	915.9	877.3	49.4

Test No.	Config. No.	Time, s	TBA, °C	TBB, °C	TBC, °C	TBD, °C	TBE, °C	TBF, °C	TBG, °C
1524B	150	420	1044.6	884.7	209.7	921.1	902.8	191.0	—
		450	810.2	896.9	462.7	865.9	913.6	366.7	—
1524C	150	0	36.8	28.0	27.1	33.8	27.9	33.7	
		60	84.2	28.1	27.2	77.2	27.9	32.6	
		90	380.9	28.2	27.2	525.2	27.9	32.6	
		120	912.0	28.2	27.2	856.2	27.9	32.5	
		150	886.8	28.4	27.2	881.1	28.0	32.4	
		180	888.7	31.9	27.2	889.9	29.1	32.3	
		210	902.4	63.3	27.3	892.9	36.9	32.2	
		240	932.0	871.8	27.3	889.4	307.9	32.2	
		270	821.7	878.2	27.3	862.6	923.7	32.2	
		300	776.4	896.8	27.5	842.2	920.0	32.8	
		330	781.3	878.2	30.3	825.7	920.9	38.9	
		360	763.6	900.0	540.8	826.8	918.3	281.1	
		390	776.0	912.0	785.7	828.0	925.5	528.3	
		420	771.3	942.7	575.2	824.8	950.9	595.7	
		450	763.4	969.9	496.2	832.9	972.6	305.6	
1525A	151	0	27.5	26.0	25.8	25.5	24.2	27.9	26.7
		120	36.4	26.6	26.2	28.4	24.9	28.5	292.8
		240	43.0	27.1	26.6	77.4	25.2	28.8	362.3
		360	48.6	26.7	26.8	80.5	24.8	29.0	322.8
		480	54.4	26.3	26.1	78.6	24.4	28.1	349.4
		600	61.8	26.8	26.5	78.1	24.8	28.5	347.1
		720	69.4	27.3	26.9	77.1	25.4	29.1	327.7
		840	77.4	27.7	27.4	77.4	25.8	29.3	356.6
		960	85.0	27.9	27.6	77.0	25.8	29.7	353.4
		1080	91.7	27.4	27.1	75.8	25.6	29.1	341.1
		1200	98.6	27.4	27.6	76.2	26.2	29.6	356.8
		1320	105.1	28.4	28.0	76.7	26.7	30.1	346.7
		1440	110.3	27.5	27.2	76.0	25.4	27.6	328.3

Test No.	Config. No.	Time, s	TBA, °C	TBB, °C	TBC, °C	TBD, °C	TBE, °C	TBF, °C	TBG, °C
1525A	151	1560	116.6	27.5	27.1	75.6	25.8	29.2	333.3
		1680	122.1	28.0	27.5	75.8	26.3	29.7	333.4
		1800	127.6	28.1	27.9	75.6	26.8	30.1	333.9
		1860	127.5	28.9	28.2	35.6	27.2	30.4	75.1
1525B	152	0	27.9	28.3	28.6	28.9	27.4	31.3	30.3
		5	28.7	28.3	28.6	32.1	27.5	31.3	71.8
		10	31.1	28.2	28.5	41.9	27.6	31.3	181.8
		15	33.4	28.2	28.4	52.0	27.6	31.3	278.6
		20	35.2	28.3	28.4	60.8	27.6	31.3	349.2
		25	36.6	28.3	28.5	68.6	27.5	31.3	409.5
		30	38.0	28.3	28.4	75.5	27.6	31.2	461.8
		35	39.1	28.3	28.5	81.5	27.6	31.1	497.3
		40	40.1	28.4	28.6	87.7	27.6	31.3	538.1
		41	40.5	28.2	28.4	88.8	27.6	31.3	546.1
		42	40.8	28.2	28.3	90.3	27.5	31.2	554.7
		43	41.1	28.2	28.3	71.8	27.5	31.2	561.8
		44	65.3	65.4	89.8	109.6	68.2	117.3	529.2
		45	66.7	67.6	94.7	107.6	67.3	115.4	514.7
		50	59.6	69.9	111.3	104.8	67.3	108.4	442.2
1525C	152	0	FLAME-THROUGH AT IGNITION						
1526A	153	0	24.3	—	—	—	—	—	—
		120	80.8	—	—	—	—	—	—
		240	83.0	—	—	—	—	—	—
		360	84.9	—	—	—	—	—	—
		480	86.0	—	—	—	—	—	—
		600	88.1	—	—	—	—	—	—
		720	89.0	—	—	—	—	—	—
		840	92.4	—	—	—	—	—	—
		960	92.5	—	—	—	—	—	—

Test No.	Config. No.	Time, s	TBA, °C	TBB, °C
1526A	153	1080	74.0	—
		1200	75.5	—
		1320	77.3	—
		1440	77.8	—
		1560	78.4	—
		1680	100.0	—
		1800	102.2	—
		1860	65.6	—
1526B	154	0	32.4	30.9
		120	45.9	71.8
		240	47.6	92.2
		360	48.8	94.2
		480	47.8	92.4
		600	48.3	95.9
		720	49.8	97.0
		840	50.3	99.2
		960	51.1	100.5
		1080	51.6	101.4
		1200	51.3	101.0
		1320	52.4	102.0
		1440	53.7	108.8
		1560	54.4	107.8
		1680	54.4	107.3
		1800	54.8	110.5
		1860	325	65.6
1527A	155	0	26.5	
		120	97.2	
		240	350.0	
		360	274.8	
		480	298.5	—

Test No.	Config. No.	Time, s	TBA, °C	TBB, °C
1527A	155	600	290.2	—
		720	266.2	—
		840	241.2	—
		960	[illegible]	—
		1080	226.8	—
		1200	301.3	—
		1320	323.6	—
		1440	337.0	—
		1560	279.8	—
		1680	267.6	—
		1800	206.3	—
		1860	110.3	—
1527B	156	0	36.6	38.4
		120	59.2	158.0
		240	61.0	[illegible]
		360	[illegible]	187.3
		480	62.0	195.6
		600	62.1	191.6
		720	63.4	199.2
		840	64.2	202.8
		960	65.8	194.7
		1080	65.4	196.9
		1200	65.5	188.7
		1320	64.0	179.0
		1440	65.6	188.1
		1560	65.3	181.7
		1680	66.0	194.2
		1800	67.1	204.3
		1880	67.7	207.9
		1860	47.7	103.5

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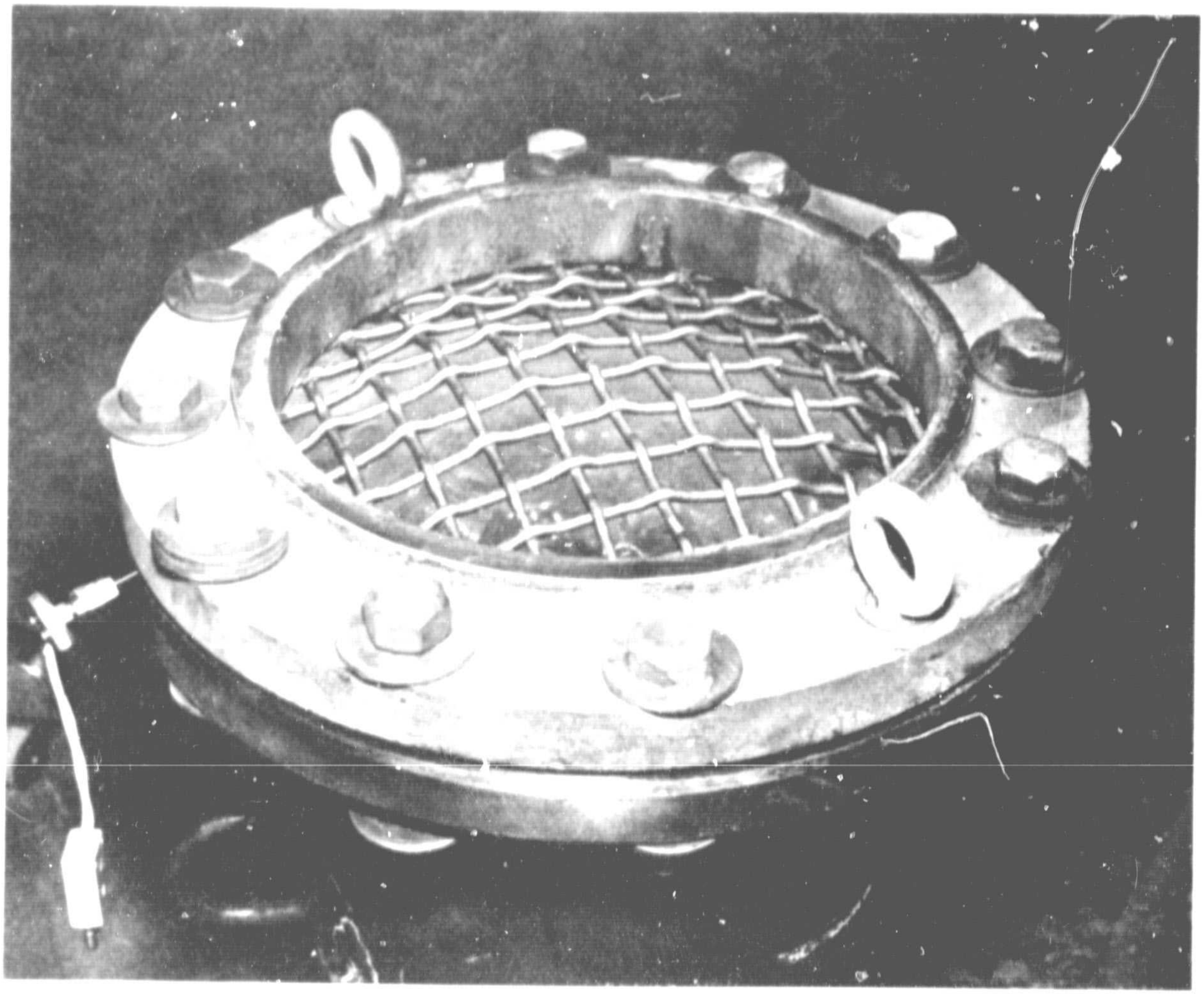

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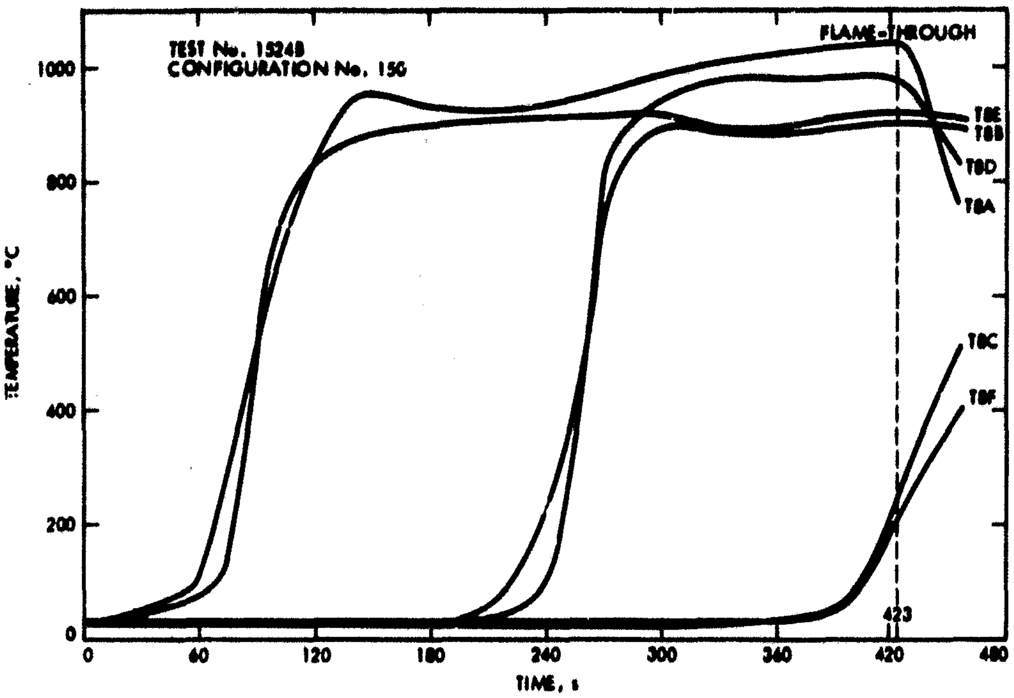

Figure 9-16. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester Ethylene/Air Mixture Sustained Burning First Test Results

2. Packed Bed of Aluminum Ballast Rings Arrester

This is the same arrester test assembly (Test Configuration No. 152) shown in Figure 9-13. The test flow conditions were the same as those described in Paragraph A-6 of this section. In the first test (No. 1525B) the temperature on the upstream face of the retainer screen (T8G) increased rapidly, reaching the spontaneous ignition level of 490°C (914°F) after only 35 seconds of operation. Flame penetration occurred at 43 seconds when the screen temperature reached 560°C (1040°F). The bed of aluminum Ballast rings remained at the inlet ethylene/air mixture temperature with only the downstream center of the bed (T8A) receiving any measurable radiation from the sustained burning. Flame penetration through the retainer screen was followed by a detonation in the inlet piping. Flame speeds measured in the witness section, which was just upstream of the test arrester section, were at the detonation velocity of around 1830 m/s (6000 ft/s). This would indicate that the penetrating flame had made the transition from deflagration to detonation within the length of the packed bed arrester. A plot of the test results is presented in Figure 9-18. Posttest inspection of the arrester revealed some distortion and discoloration of the retainer grid and screen assembly caused by internal pressure developed during the detonation.

The above test was repeated at the same test conditions and with the same arrester test assembly. This second test (No. 1525C) resulted in a detonation immediately after ignition. Posttest disassembly and inspection of the packed bed arrester revealed that the screen retainer had been impacted in several

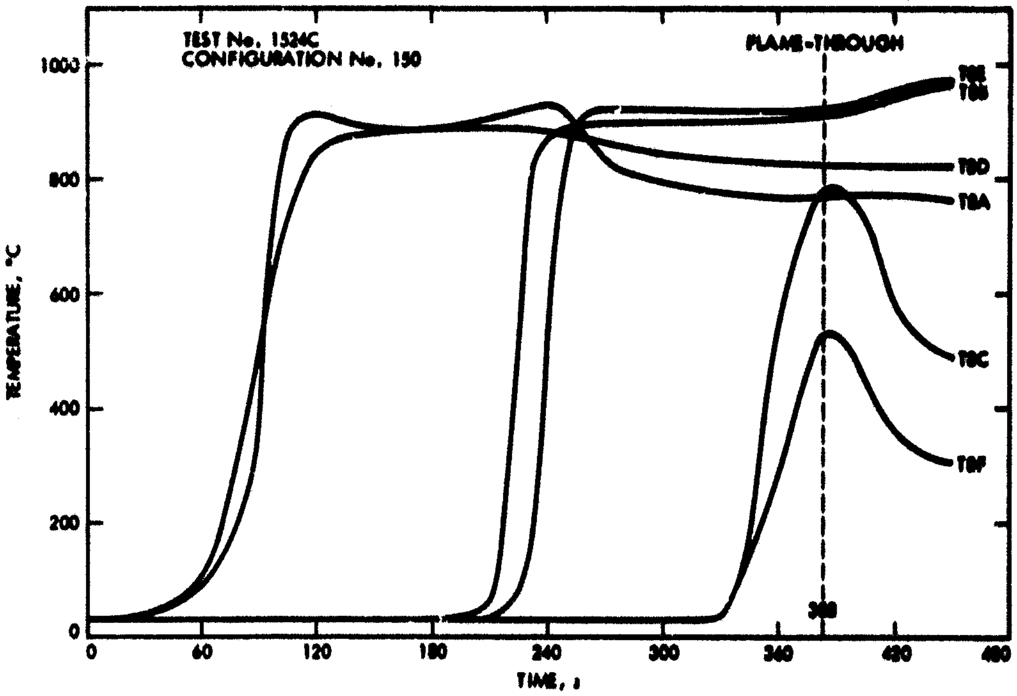

Figure 9-17. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester Ethylene/Air Mixture Sustained Burning Second Test Results

places by Ballast rings causing punctures as shown in Figure 9-19. The undetected damage to the screen was probably initiated to a lesser extent during the first sustained burning test that resulted in a detonation. These small punctures allowed flame penetration without heat-up on the second test and the subsequent detonation enlarged the holes to the size shown.

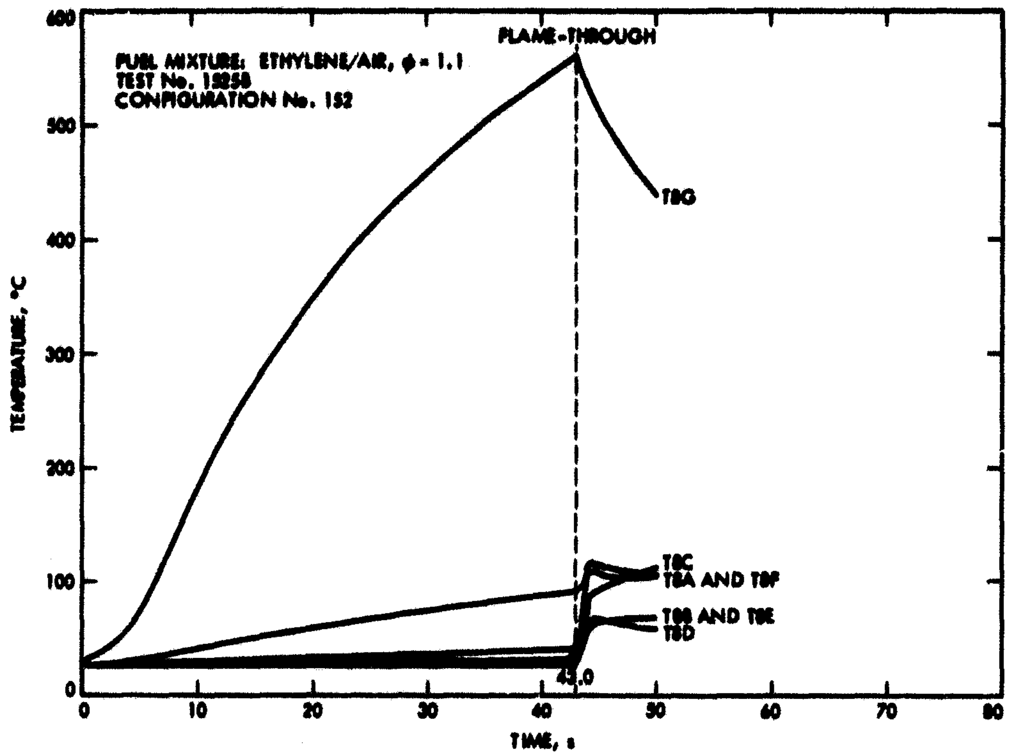

Figure 9-18. Packed Bed of Ballast Rings with Single 30-Mesh Screen Arrester Ethylene/Air Sustained Burning Test Results

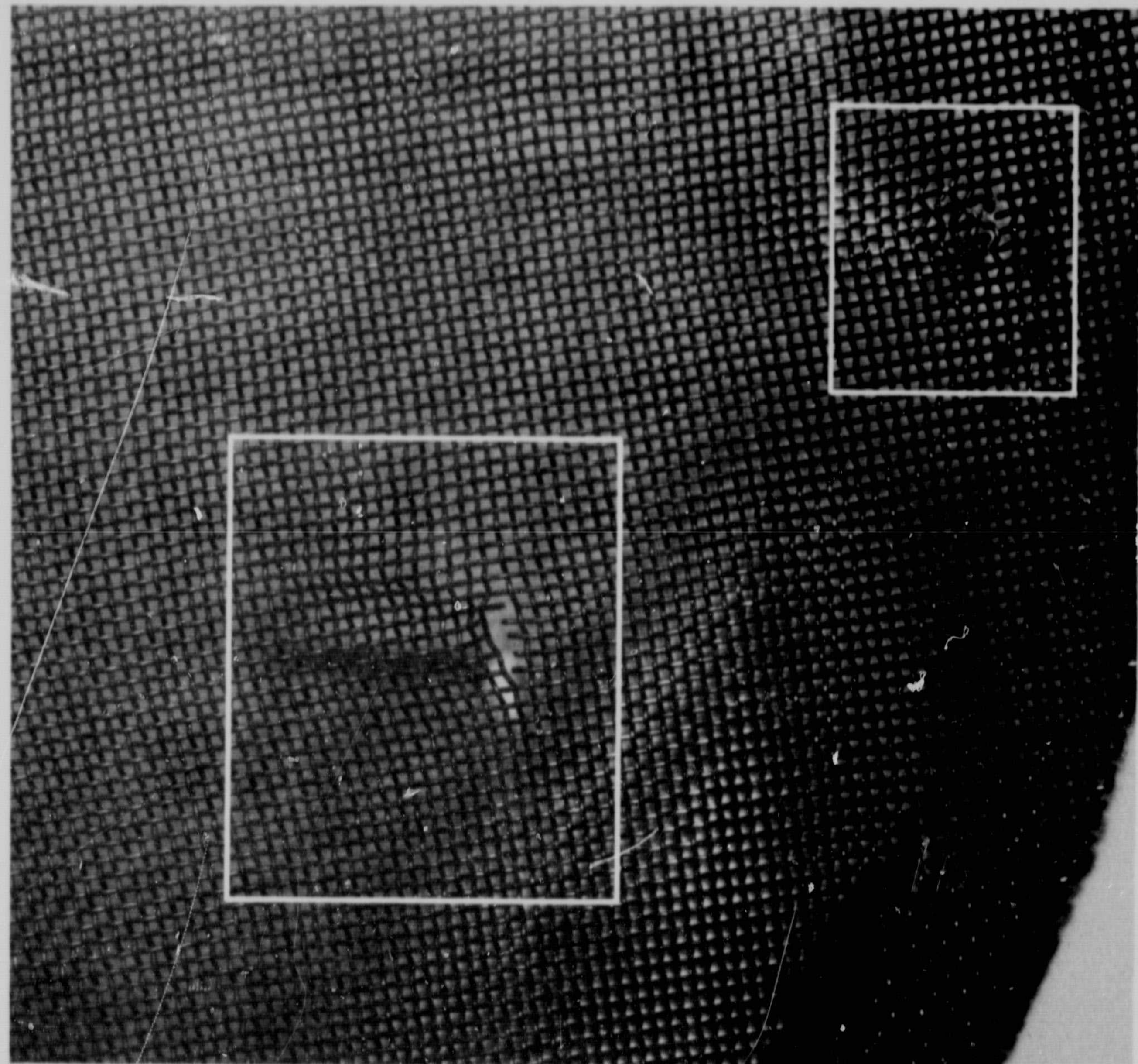

Figure 9-19. Single 30-Mesh Screen Retainer from the Packed Bed of Ballast Rings Arrester Posttest

SECTION X

CONCLUSIONS

The following conclusions have been reached from the test results of this experimental evaluation of flame arrester devices in a simulated fuel storage tank vent stack installation discharging eight types of combustible fuel/air mixtures, including: (1) propane, (2) ethylene, (3) gasoline, (4) methanol, (5) toluene, (6) diethyl ether, (7) butane, and (8) acetaldehyde. The test flame arresters were mounted on the end of a 15.2-cm- (6-in.-) diameter pipe vent located in an unconfined one-atmosphere environment. The standard test condition used an injection equivalence ratio from 1.0 to 1.2 to produce the theoretical maximum flame speed for the particular fuel/air mixture in use; the fuel/air mixture temperature ranged from 10 to 38°C (50 to 100°F), and the inlet piping nominal flow velocity was 1.52 m/s (5 ft/s).

(1) An ignition source upstream near the flame arrester and in the center of the exhaust plume produced the highest flashback flame speed for a flame propagating upstream in the direction of the arrester.

(2) Ethylene/air mixture produced the highest average flashback flame speed of 6.60 m/s (21.65 ft/s), ranging from 4.86 to 10.66 m/s (15.94 to 34.98 ft/s).

(3) Butane/air mixture produced the lowest average flashback flame speed of 3.62 m/s (11.88 ft/s), ranging from 2.92 to 4.25 m/s (9.58 to 13.94 ft/s).

(4) Flashback flames from the typical bulk cargo fuels tested will propagate in an open environment, such as the deck of a transport vessel, but will not produce a detonation unless they penetrate an opening leading into a fuel cargo tank.

(5) The single 30-mesh stainless-steel screen arrester was effective in quenching flashback flames from all eight fuel/air mixtures tested.

(6) The dual 20-mesh stainless-steel screen arrester was effective in quenching flashback flames from all eight fuel/air mixtures tested except the ethylene/air mixture, where the flame speed was 4.86 m/s (15.94 ft/s) or faster.

(7) Damage to a screen flame arrester from a puncture, tear, or corrosion that results in holes larger than the original mesh size renders the screen useless in quenching a flashback flame. The damaged screen should be replaced to restore the arrester's effectiveness.

(8) The spiral-wound, crimped stainless-steel ribbon arrester was effective in quenching flashback flames from the propane, ethylene, and gasoline fuel/air mixtures tested, and would probably quench the other five fuel/air mixtures listed.

(9) The packed bed of aluminum Ballast rings arrester with single 30-mesh stainless-steel screen retainers was effective in quenching flashback flames from the propane, ethylene, and gasoline fuel/air mixtures tested, and would probably quench the other five fuel/air mixtures listed.

(10) The packed bed of aluminum Ballast rings arrester without the single 30-mesh screen retainer was not effective in quenching flashback flames from gasoline/air mixtures, and would probably not quench the other seven fuel/air mixtures listed.

(11) The test configurations for the single 30-mesh screen arrester, the dual 20-mesh screen arrester, the spiral-wound, crimped ribbon arrester, and the packed bed of Ballast rings arrester withstood all flashback flame testing without any structural damage and only slight discoloration from the short duration of flame impingement (approximately 25 seconds).

(12) The single 30-mesh screen arrester and the dual 20-mesh screen arrester withstood flames from propane/air mixtures for 30 minutes without structural damage and only slight discoloration of the screen wire. The fuel/air mixture flow velocity through the openings in the screen ranged from 1.2 to 4.1 m/s (3.9 to 13.5 ft/s), depending on the size of the arrester test assembly. In each configuration, the screens reached a condition approaching thermal equilibrium after approximately 300 seconds where the temperature was well below the spontaneous ignition temperature for the propane/air mixture. It is concluded that the sustained burning conditions on these arresters could have continued for an indefinite period of time.

(13) The equilibrium temperature on the surface of a screen flame arrester at sustained burning conditions is a function of flow velocity of the fuel/air mixture passing through the screen; the lower the velocity, the higher the equilibrium temperature. It is possible that at very low flow-through velocities the temperature of the screen would increase to the spontaneous ignition temperature of the fuel and the flame could penetrate the screen arrester.

(14) The spiral-wound, crimped ribbon arrester withstood flames from the propane/air mixture for 30 minutes. During this time, the flame propagated into part of the depth of the core element, causing distortion and discoloration of the stainless-steel ribbon. Thermal equilibrium within the core element was not achieved during the 30 minutes of testing as the temperatures measured inside the ribbon windings continued to increase above the spontaneous ignition temperature for propane/air mixtures. It is concluded that the flame would have eventually penetrated the arrester, given sufficient time. Sustained burning from the ethylene/air mixture did penetrate through this arrester on two tests of 423 and 383 seconds. Therefore, the ability of this type of flame arrester to withstand sustained burning is highly dependent on the flame speed and the spontaneous ignition temperature of the fuel/air mixture.

(15) The packed bed of Ballast rings arrester with a single 30-mesh screen retainer withstood flames from the propane/air mixture for 30 minutes. The results were very similar to those obtained from the single 30-mesh screen arrester, and it is apparent that the bed of rings has little or no influence on the performance of this arrester configuration. Sustained burning from the ethylene/air mixture did penetrate through this arrester in only 43 seconds on one test, resulting in a deflagration-to-detonation transition within the bed of rings. The retainer screen was damaged by impacts from the bed of rings, and this damage allowed the flame to penetrate immediately after ignition on a repeat test. It is concluded that the packed bed of rings arrester with a single 30-mesh screen is no more effective than a single 30-mesh screen in withstanding and quenching flashback flames.

SECTION XI

RECOMMENDATIONS

Based upon the results of this test program, the following recommendations are made regarding the selection and installation of flame arresting devices on fuel storage tank vent stacks in a marine environment:

(1) Based upon flame quenching capability, structural durability, and a low susceptibility to corrosion and fouling, the following flame arrester devices have been found effective in preventing flashback flames in an open environment from entering vent openings of a cargo tank containing typical bulk fuels: (1) single 30-mesh stainless-steel screen, (2) dual 20-mesh stainless-steel screen, (3) spiral-wound, crimped stainless steel ribbon, and (4) packed bed of aluminum Ballast rings with single 30-mesh stainless-steel screen retainers. Ethylene, which is a gas at ambient temperature and pressure, is not a typical bulk cargo fuel.

(2) Based upon the ability to withstand 30 minutes of continuous burning of a propane/air mixture, the following flame arrester devices have been found effective in sustaining the flame from typical bulk cargo fuels: (1) single 30-mesh stainless-steel screen, (2) dual 20-mesh stainless-steel screen, (3) spiral-wound, crimped stainless-steel ribbon, and (4) packed bed of Ballast rings with single 30-mesh stainless steel screen retainers. Spiral-wound, crimped metal ribbon arresters appear to have a finite time duration for sustained burning conditions, and should therefore be evaluated for the specific fuel and at the most severe condition of the intended applications. None of the flame arrester devices tested is effective in sustaining the flame from an ethylene/air mixture for 30 minutes duration.

(3) Based upon the inverse relationship between the equilibrium temperature of a screen flame arrester at sustained burning conditions and the fuel/air mixture flowthrough velocity, it is recommended that in fuel transfer operations the rate of fuel flow should be fast enough to keep the exhaust velocity of vented flammable mixture well above the laminar burning velocity of the fuel being transferred. In the event of a flashback flame, this safety precaution will aid in keeping the screen flame arrester on the vent from over-heating by a sustained flame.

(4) The selection of a location for the flame arrester device on the vent stack should be limited to the very end of the pipe. The flame quenching ability of the arrester is reduced by any length of pipe, housing, or mechanical device downstream of the arrester. Screen-type flame arresters are effective only if they are undamaged by punctures or tears in the wire mesh and there are no gaps or holes around the periphery larger than the openings specified for the 20- or 30-mesh screen. All flame arrester devices should be periodically inspected for damage and cleaned to remove fouling and corrosion.

(5) The selection of materials used in the construction of arresters should be based on their compatibility with the local environment and the fuel vapors to be encountered. However, stainless steel is recommended.

The data and experience obtained from these flashback flame and sustained burning tests is limited to those fuel and air mixtures tested in a 15.2-cm- (16-in.-) diameter pipe size. It is recommended that extrapolation of this data should be limited to the following:

(1) Application to other fuels should be limited to those hydrocarbon fuels that have similar combustion characteristics to those fuels tested.

(2) Applications scaled down to pipe sizes smaller than 15.2-cm (6-in.) diameter are considered to be conservative.

(3) Scaled-up applications should be limited to pipe sizes no larger than a 20.3-cm (8-in.) diameter, providing adequate consideration is given to structural strength.

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APPENDIX A

TEST CONFIGURATION LOG

Configuration No.	Test No.	Description
100 to 112	1488 to 1495	The first thirteen test configurations were evolved during the facility checkout tests. They included the preliminary installation of a subscale flame chamber that was later replaced by the full-scale flame chamber and the exhaust collector burn stack. Flame sensors on the flame chamber outer wall were repositioned from the horizontal center line to the top center line. Three igniter positions used in the flame chamber were (1) upstream, (2) middle, and (3) downstream. An aluminum flame shield was installed on the inlet piping upstream of the flame arrester test section. Also, a second aluminum flame shield was installed in front of the downstream flame chamber frangible diaphram. Fuels used on these checkout tests were gasoline and commercial grade propane. The test arresters included both the dual 20-mesh screens and the single 30-mesh screen.
113	1496 (A-C)	This test configuration is shown in Figure 7-2. Flame arrester: dual 20-mesh screens Fuel: propane Igniter position: upstream
114	1497 (A-C)	Flame arrester: dual 20-mesh screens Fuel: propane Igniter position: downstream
115	1498 (A-D)	Flame arrester: single 30-mesh screen Fuel: propane Igniter position: downstream
116	1499 (A-C)	Flame arrester: single 30-mesh screen Fuel: propane Igniter position: upstream
117	1500 (A-C)	Flame arrester: single 30-mesh screen Fuel: ethylene Igniter position: upstream
118	1501 (A)	Changed the exhaust collector burn-stack flame arrester from an Amal spiral-wound, crimped stainless-steel ribbon to a Shand and Jurs spiral-wound, crimped aluminum ribbon assembly. Flame arrester: single 30-mesh screen Fuel: ethylene Igniter position: upstream

Configuration No.	Test No.	Description	
119	1501 (B-D)	Flame arrester:	single 30-mesh screen
		Fuel:	ethylene
		Igniter position:	downstream
120	1502 (A)	Flame arrester:	none
		Fuel:	ethylene
		Igniter position:	downstream
121	1502 (B-D)	Flame arrester:	dual 20-mesh screens
		Fuel:	ethylene
		Igniter position:	downstream
122	1503 (A-C)	Flame arrester:	dual 20-mesh screens
		Fuel:	ethylene
		Igniter position:	upstream
123	1504 (A-C)	Flame arrester:	crimped ribbon
		Fuel:	propane
		Igniter position:	upstream

NOTE: All of the following tests were made with the igniter located in the upstream position unless otherwise noted.

Configuration No.	Test No.	Description	
124	1505 (A-D)	Flame arrester:	crimped ribbon
		Fuel:	ethylene
125	1506 (A-D)	Flame arrester:	crimped ribbon
		Fuel:	gasoline
126	1507 (A-D)	Flame arrester:	none
		Fuel:	gasoline
127	1507 (C)	Flame arrester:	single 30-mesh screen
	1508 (A-B)	Fuel:	gasoline
128	1508 (C-E)	Flame arrester:	dual 20-mesh screens
		Fuel:	gasoline
129	1509 (A-C)	Flame arrester:	packed bed of rings
		Fuel:	gasoline
130	1510 (A-C)	Flame arrester:	packed bed of rings with single 30-mesh screen
		Fuel:	gasoline

Configuration No.	Test No.	Description	
131	1511 (A-D)	Flame arrester:	packed bed of rings with single 30-mesh screen
		Fuel:	ethylene
132	1512 (A-C)	Flame arrester:	packed bed of rings with single 30-mesh screen
		Fuel:	propane
133	1513 (A-C)	Flame arrester:	single 30-mesh screen
		Fuel:	methyl alcohol
134	1513 (D)	Flame arrester:	none
		Fuel:	methyl alcohol
135	1514 (A-C)	Flame arrester:	dual 20-mesh screens
		Fuel:	methyl alcohol
136	1515 (A-C)	Flame arrester:	dual 20-mesh screens
		Fuel:	toluene
137	1515 (D)	Flame arrester:	none
		Fuel:	toluene
138	1516 (A-D)	Flame arrester:	single 30-mesh screen
		Fuel:	toluene
139	1517 (A-C)	Flame arrester:	single 30-mesh screen
		Fuel:	diethyl ether
140	1517 (D)	Flame arrester:	none
		Fuel:	diethyl ether
141	1518 (A-C)	Flame arrester:	dual 20-mesh screens
		Fuel:	diethyl ether
142	1519 (A-D)	Flame arrester:	dual 20-mesh screens
		Fuel:	butane
143	1519 (E)	Flame arrester:	none
		Fuel:	butane
144	1520 (A-C)	Flame arrester:	single 30-mesh screen
		Fuel:	butane
145	1521 (A-C)	Flame arrester:	single 30-mesh screen
		Fuel:	acetaldehyde

Configuration No.	Test No.	Description
146	1521 (D)	Flame arrester: none Fuel: acetaldehyde
147	1522 (A-C)	Flame arrester: dual 20-mesh screens Fuel: acetaldehyde
148	1523 (A-B)	Changed the test assembly to the sustained burning test configuration. Flame arrester: crimped ribbon Fuel: propane
149	1524 (A)	Changed the thermocouples in the test arrester from open tip ungrounded to closed-end grounded. Flame arrester: crimped ribbon Fuel: propane
150	1524 (B-C)	Flame arrester: crimped ribbon Fuel: ethylene
151	1525 (A)	Flame arrester: packed bed of rings with single 30-mesh screen Fuel: propane
152	1525 (B-C)	Flame arrester: packed bed of rings with single 30-mesh screen Fuel: ethylene
153	1526 (A)	Flame arrester: 15.2-cm- (6.0-in.-) diameter single 30-mesh screen Fuel: propane
154	1526 (B)	Flame arrester: 15.2-cm- (6.0-in.-) diameter dual 20-mesh screens Fuel: propane
155	1527 (A)	Flame arrester: 25.4-cm- (10.0-in.-) diameter single 30-mesh screen Fuel: propane
156	1527 (B)	Flame arrester: 25.4-cm- (10.0-in.-) diameter dual 20-mesh screens Fuel: propane

APPENDIX B

TABULAR SUMMARY OF STEADY-STATE MEASURED AIR AND FUEL SYSTEM TEST CONDITIONS

LIQUID FUELS

Test No.	Config. No.	PBO, kN/m²	DPO, kN/m²	TO1, °C	PFL, kN/m²	TFL °F	FMF, Hz	PV1, kN/m²	TV1, °C	TV2, °C	TMF, °C	PM1, kN/m²	TM1, °C	T14, °C	TB1, °C	PA1, kN/m²	DPA1, N/m²	DPA2, N/m²	PAMB, kN/m²	VA, m/s	MA, kg/h	MF, kg/h	A/F Ratio	φ E.R.	HCA E.R.
[illegible]	[illegible]	125.76	[illegible]	68.6	[illegible]	25.6	178.7	110.9	[illegible]	[illegible]	104.8	93.68	47.0	[illegible]	[illegible]	[illegible]	3.0	[illegible]	[illegible]	1.573	[illegible]	[illegible]	[illegible]	[illegible]	.77
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	111.0	[illegible]	[illegible]	[illegible]	[illegible]	47.2	[illegible]	[illegible]	[illegible]	[illegible]	9.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.92
B	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.11	[illegible]
C	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	111.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	24.1	[illegible]	[illegible]	7.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	114	[illegible]	[illegible]	[illegible]	2216	13.4	[illegible]	111.8	125.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
B	114	[illegible]	[illegible]	71.1	2241	16.2	[illegible]	[illegible]	124.7	[illegible]	106.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	7.7	7.7	[illegible]	[illegible]	[illegible]	7.571	[illegible]	.11	[illegible]
C	114	[illegible]	[illegible]	71.1	2245	[illegible]	[illegible]	111.8	[illegible]	[illegible]	108.7	[illegible]	[illegible]	[illegible]	23.4	[illegible]	[illegible]	9.0	[illegible]	1.527	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2210	[illegible]	[illegible]	[illegible]	[illegible]	252.7	105.8	[illegible]	[illegible]	[illegible]	18.1	[illegible]	[illegible]	6.2	[illegible]	1.447	[illegible]	7.271	14.17	[illegible]	[illegible]
B	[illegible]	[illegible]	[illegible]	[illegible]	1766	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	24.0	[illegible]	6.9	7.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.13	[illegible]
C	115	[illegible]	[illegible]	[illegible]	[illegible]	17.7	166.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	14.24	1.10	[illegible]
D	[illegible]	[illegible]	[illegible]	67.4	[illegible]	17.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	45.7	[illegible]	22.4	[illegible]	6.7	6.7	[illegible]	1.481	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	74.1	[illegible]	15.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	24.6	[illegible]	[illegible]	[illegible]	9.0	[illegible]	[illegible]	[illegible]	7.217	[illegible]	[illegible]	[illegible]
B	116	[illegible]	[illegible]	[illegible]	[illegible]	16.7	[illegible]	[illegible]	124.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.3	9.0	[illegible]	1.464	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
C	116	[illegible]	[illegible]	[illegible]	[illegible]	17.9	[illegible]	[illegible]	123.1	257.7	[illegible]	[illegible]	[illegible]	[illegible]	24.7	[illegible]	[illegible]	[illegible]	[illegible]	1.510	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	178.1	[illegible]	115.7	242.3	[illegible]	[illegible]	[illegible]	19.4	15.1	[illegible]	37.2	37.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
B	[illegible]	[illegible]	[illegible]	[illegible]	2145	11.8	[illegible]	110.5	127.7	[illegible]	96.7	[illegible]	[illegible]	17.7	17.7	[illegible]	[illegible]	37.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.82
C	[illegible]	[illegible]	[illegible]	[illegible]	2159	11.1	171.4	[illegible]	125.7	[illegible]	75.8	[illegible]	[illegible]	17.7	[illegible]	[illegible]	35.9	35.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.85
[illegible]	125	[illegible]	[illegible]	61.1	[illegible]	3.11	117.5	103.9	[illegible]	541.3	[illegible]	[illegible]	[illegible]	[illegible]	15.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
B	[illegible]	[illegible]	[illegible]	[illegible]	770.7	7.8	117.5	106.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	41.4	42.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
C	[illegible]	127.81	[illegible]	[illegible]	767.9	11.4	117.8	[illegible]	[illegible]	546.4	176.2	93.57	[illegible]	[illegible]	30.7	[illegible]	42.7	44.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
D	[illegible]	127.51	[illegible]	71.8	774.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	35.5	27.3	[illegible]	40.7	[illegible]	[illegible]	1.518	[illegible]	[illegible]	[illegible]	[illegible]	0.70
[illegible]	[illegible]	127.74	[illegible]	57.7	[illegible]	[illegible]	121.7	103.5	[illegible]	541.9	[illegible]	[illegible]	40.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
B	[illegible]	127.41	[illegible]	57.4	768.4	[illegible]	[illegible]	101.7	170.3	[illegible]	[illegible]	93.51	41.8	26.1	[illegible]	[illegible]	[illegible]	4.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
C	127	128.01	[illegible]	61.8	[illegible]	15.4	120.1	101.6	209.6	[illegible]	[illegible]	[illegible]	[illegible]	20.7	[illegible]	[illegible]	6.7	7.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.71
[illegible]	127	[illegible]	[illegible]	66.1	[illegible]	14.7	[illegible]	103.3	[illegible]	519.1	[illegible]	[illegible]	[illegible]	[illegible]	17.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.71
B	[illegible]	[illegible]	[illegible]	65.4	786.7	14.4	124.5	101.7	214.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	16.2	[illegible]	7.6	[illegible]	[illegible]	1.480	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
C	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17.8	118.0	[illegible]	[illegible]	[illegible]	149.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	7.7	7.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.17	[illegible]
D	[illegible]	127.44	[illegible]	61.3	786.5	17.3	[illegible]	103.7	[illegible]	552.7	[illegible]	[illegible]	[illegible]	27.7	[illegible]	[illegible]	7.6	7.0	[illegible]	[illegible]	[illegible]	[illegible]	15.41	[illegible]	[illegible]
E	[illegible]	127.34	[illegible]	[illegible]	781.9	[illegible]	[illegible]	101.8	[illegible]	547.7	145.2	[illegible]	[illegible]	[illegible]	19.7	[illegible]	[illegible]	[illegible]	[illegible]	1.448	[illegible]	[illegible]	[illegible]	[illegible]	0.70
[illegible]	[illegible]	[illegible]	[illegible]	54.8	757.7	10.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	57.0	[illegible]	[illegible]	[illegible]	[illegible]	24.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
B	127	[illegible]	[illegible]	[illegible]	754.0	12.6	[illegible]	[illegible]	207.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	20.7	24.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.70
C	129	127.57	[illegible]	[illegible]	761.8	10.7	[illegible]	102.8	[illegible]	531.4	136.1	[illegible]	[illegible]	21.2	13.0	[illegible]	22.1	[illegible]	[illegible]	1.441	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

LIQUID FUELS (contd)

Test No.	Config. No.	PBO, kN/m²	DPO, kN/m²	TO1, °C	PFL, kN/m²	TFL, °F	FMF, Hz	PV1, kN/m²	TV1, °C	TV2, °C	TMF, °C	PM1, kN/m²	TM1, °C	TM, °C	TB1, °C	PA1, kN/m²	DPA1, N/m²	DPA2, N/m²	PAMB, kN/m²	VA, m/s	MA, kg/h	MF, kg/h	A/F Ratio	φ E.R.	HCA E.R.
1510A	130	127.97	[illegible]	65.0	763.5	7.1	114.7	105.0	210.1	345.9	179.2	74.710	48.9	21.7	17.3	73.73	2.0	22.0	[illegible]	1.419	[illegible]	7.747	[illegible]	1.15	0.72
B	130	128.27	0.2331	62.7	768.1	13.6	118.6	104.7	207.3	346.8	169.7	74.53	51.8	27.1	23.1	74.482	24.1	24.0	[illegible]	1.434	[illegible]	[illegible]	[illegible]	1.15	0.72
C	130	128.37	0.2251	66.8	766.6	14.1	117.8	102.3	205.8	348.3	168.8	74.42	49.1	28.9	21.3	74.372	24.8	23.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.15	0.71
1512A	132	127.34	[illegible]	56.1	2177	12.1	165.3	110.4	123.8	261.1	86.6	72.784	32.8	16.6	12.8	[illegible]	20.7	20.0	[illegible]	[illegible]	[illegible]	7.376	[illegible]	1.15	0.71
B	132	127.18	[illegible]	56.8	212.7	13.4	171.7	110.6	133.2	260.7	77.8	72.834	34.2	18.2	14.1	72.784	20.0	18.6	[illegible]	1.426	[illegible]	7.571	13.49	1.16	0.69
C	132	126.86	[illegible]	56.6	2127	13.0	167.4	110.1	133.4	258.3	77.0	72.717	34.0	18.2	13.4	72.61	20.0	20.0	[illegible]	1.430	[illegible]	7.704	[illegible]	1.15	0.69
1513A	133	128.67	0.2317	64.2	682.6	7.4	248.4	181.1	182.7	425.1	135.7	73.710	45.2	24.2	16.5	[illegible]	8.27	7.65	[illegible]	[illegible]	[illegible]	6.27	6.43	1.00	0.67
B	133	128.12	0.2317	66.4	[illegible]	11.5	243.9	185.2	166.1	423.2	145.4	73.765	50.0	25.8	17.7	73.647	7.58	[illegible]	[illegible]	1.448	[illegible]	[illegible]	6.15	1.00	0.67
C	133	128.10	0.2310	66.4	606.6	12.7	246.6	187.0	165.2	421.2	143.7	[illegible]	50.6	28.4	17.2	73.742	6.80	6.10	[illegible]	1.413	[illegible]	6.06	[illegible]	1.01	0.67
D	134	127.72	0.2337	62.6	573.5	14.4	249.2	184.7	159.2	421.7	137.3	N.A.	51.3	27.7	21.5	[illegible]	3.45	2.76	[illegible]	[illegible]	[illegible]	6.12	6.21	1.02	0.70
1514A	135	127.63	0.2372	65.2	502.7	7.2	[illegible]	173.2	143.3	423.4	143.7	74.574	56.9	26.3	16.1	74.476	11.0	11.0	[illegible]	1.415	[illegible]	6.30	6.28	1.02	[illegible]
B	135	[illegible]	0.2324	67.7	472.7	13.4	249.4	181.7	142.1	427.4	140.5	74.177	58.4	31.1	23.1	74.131	12.4	11.7	74.117	1.457	[illegible]	[illegible]	[illegible]	1.03	0.70
C	135	129.27	0.2344	70.3	477.3	14.7	253.0	[illegible]	166.7	427.0	145.1	74.151	56.8	32.8	23.8	74.085	12.4	12.4	[illegible]	1.463	[illegible]	6.43	6.21	1.04	[illegible]
1515A	136	128.77	0.2317	67.8	232.5	13.2	75.3	106.7	215.3	543.7	170.7	74.496	52.6	24.5	18.6	74.372	8.46	10.3	[illegible]	1.458	[illegible]	7.777	[illegible]	[illegible]	0.70
B	136	128.50	0.2412	69.7	210.3	14.8	78.7	106.6	214.1	542.7	[illegible]	74.310	55.1	27.7	22.2	74.234	10.3	10.3	74.230	1.490	[illegible]	[illegible]	12.99	[illegible]	0.70
C	137	127.93	0.2420	74.0	216.1	18.2	76.0	102.7	220.1	543.7	184.0	74.131	55.5	32.1	25.7	74.011	10.3	12.4	[illegible]	1.428	[illegible]	7.770	12.77	1.04	0.70
D	137	127.41	[illegible]	75.8	220.0	20.7	78.6	104.2	218.0	544.7	181.5	N.A.	61.6	37.4	27.2	[illegible]	2.74	3.45	[illegible]	1.527	[illegible]	[illegible]	12.71	1.05	0.70
1516A	138	128.03	0.2303	61.4	542.2	11.3	71.3	105.5	193.0	532.3	120.2	73.507	42.7	20.7	15.7	[illegible]	5.52	6.21	73.420	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
B	138	127.78	0.2331	65.4	444.3	13.9	76.7	101.0	[illegible]	531.4	120.6	[illegible]	45.4	24.1	18.8	[illegible]	6.70	7.58	73.317	1.461	[illegible]	[illegible]	12.93	[illegible]	[illegible]
C	138	127.14	0.2272	67.1	420.5	14.6	77.2	[illegible]	174.2	532.7	114.7	73.055	37.1	[illegible]	19.4	72.977	6.90	7.58	[illegible]	1.464	[illegible]	[illegible]	12.90	[illegible]	0.71
D	138	127.09	0.2276	61.7	408.7	15.0	[illegible]	104.9	[illegible]	534.6	113.3	73.014	37.2	22.8	19.4	72.971	7.58	7.58	[illegible]	1.470	[illegible]	[illegible]	12.92	[illegible]	0.71
1517A	139	[illegible]	[illegible]	[illegible]	251.3	2.2	173.6	112.4	157.0	[illegible]	136.1	[illegible]	42.7	12.9	10.5	[illegible]	[illegible]	12.4	[illegible]	1.460	[illegible]	[illegible]	9.89	1.36	0.70
B	139	128.01	0.2317	61.7	[illegible]	[illegible]	172.8	110.8	154.8	330.1	128.1	[illegible]	46.0	17.9	15.5	[illegible]	9.65	[illegible]	[illegible]	[illegible]	[illegible]	10.73	9.97	1.19	0.69
C	139	126.97	0.2327	69.4	[illegible]	7.9	170.6	[illegible]	136.9	[illegible]	118.3	[illegible]	44.4	23.6	21.2	[illegible]	10.2	11.0	[illegible]	[illegible]	[illegible]	[illegible]	9.91	1.13	0.67
D	140	127.34	[illegible]	[illegible]	[illegible]	9.9	135.5	[illegible]	[illegible]	277.8	116.7	[illegible]	47.0	26.4	[illegible]	[illegible]	0	0	[illegible]	[illegible]	[illegible]	[illegible]	9.89	1.13	0.77
1518A	141	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	138.5	[illegible]	[illegible]	278.0	115.6	[illegible]	41.6	15.8	10.1	[illegible]	6.87	7.38	[illegible]	[illegible]	[illegible]	[illegible]	9.67	1.16	0.71
B	141	[illegible]	[illegible]	[illegible]	[illegible]	11.4	176.0	115.8	140.1	[illegible]	115.5	[illegible]	42.1	18.8	14.8	[illegible]	7.58	6.27	[illegible]	[illegible]	[illegible]	[illegible]	9.65	1.16	0.71
C	141	127.34	0.2411	[illegible]	[illegible]	14.3	170.1	111.5	127.1	[illegible]	109.0	[illegible]	48.7	25.1	17.5	[illegible]	4.83	4.83	[illegible]	[illegible]	[illegible]	10.92	9.89	1.19	0.72
1519A	142	[illegible]	[illegible]	[illegible]	211.9	13.2	138.9	[illegible]	[illegible]	[illegible]	[illegible]	74.124	40.0	15.8	14.2	[illegible]	2.76	2.45	[illegible]	[illegible]	[illegible]	7.324	12.93	1.11	0.78
B	142	[illegible]	[illegible]	[illegible]	2133	14.3	146.7	[illegible]	137.5	[illegible]	[illegible]	[illegible]	44.6	23.7	19.0	[illegible]	4.83	5.52	[illegible]	[illegible]	[illegible]	[illegible]	12.69	1.13	0.75
C	142	128.03	[illegible]	[illegible]	2150	16.1	151.3	107.8	[illegible]	257.4	115.3	[illegible]	47.2	29.5	[illegible]	[illegible]	5.52	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	13.70	1.13	0.75
D	143	127.81	0.2411	[illegible]	2141	16.6	140.2	105.6	141.1	261.1	120.2	74.241	48.7	27.7	25.3	[illegible]	6.21	[illegible]	[illegible]	[illegible]	[illegible]	7.590	13.91	1.11	0.75

LIQUID FUELS (contd)

Test No	Config. No.	PBO, kN/m^2	DPO, kN/m^2	TO1, °C	PFL, kN/m^2	TFL °F	FMF, Hz	PV1, kN/m^2	TV1, °C	TV2, °C	TMF °C	PM1, kN/m^2	TM1, °C	T14, °C	TB1 °C	PA1, kN/m^2	DPA1, N/m^2	DPA2, N/m^2	PAMB, kN/m^2	VA, m/s	MA, kg/h	MF, kg/h	A/F Ratio	φ ER	HCA ER
1519E	143	127.56	2348	[illegible]	2121	[illegible]	157.2	[illegible]	138.5	267.2	115.1	74.226	61.3	32.4	29.2	74.151	2.07	[illegible]	74.151	[illegible]	84.72	[illegible]	13.57	1.14	0.78
1520A	144	[illegible]	2258	53.7	2133	15.8	152.1	105.7	131.8	[illegible]	[illegible]	72.144	[illegible]	[illegible]	17.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	13.43	1.15	0.80
C	144	127.59	2255	57.5	2217	15.6	198.1	105.7	132.2	[illegible]	[illegible]	72.401	[illegible]	21.7	17.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	13.57	1.14	0.80
C	144	[illegible]	2241	56.4	2174	15.9	198.5	108.3	130.2	254.2	102.0	[illegible]	[illegible]	17.7	16.4	[illegible]	7.58	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	13.59	1.14	0.79
1521A	145	127.37	2251	66.7	377.9	17.7	203.9	147.5	122.1	[illegible]	121.8	74.436	42.1	[illegible]	[illegible]	74.441	[illegible]	[illegible]	74.427	[illegible]	[illegible]	[illegible]	6.83	1.16	0.63
B	145	[illegible]	2327	68.1	[illegible]	13.2	201.7	139.7	56.2	[illegible]	[illegible]	74.427	[illegible]	26.1	[illegible]	74.427	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.95	1.13	0.64
C	145	[illegible]	2462	68.7	424.4	[illegible]	214.0	142.3	49.4	[illegible]	[illegible]	74.129	51.4	[illegible]	[illegible]	74.131	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.90	1.14	0.62
D	146	127.90	2434	71.7	501.5	[illegible]	210.9	149.3	150.4	[illegible]	125.4	74.022	[illegible]	34.1	[illegible]	74.020	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.83	1.15	0.60
1522A	147	[illegible]	2302	66.5	1124	14.5	209.6	141.5	125.7	[illegible]	[illegible]	74.246	[illegible]	[illegible]	[illegible]	74.241	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.77	1.17	0.59
B	147	127.87	2310	70.3	1161	17.0	206.5	141.3	125.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.82	1.15	0.66
C	147	[illegible]	2221	67.6	1156	17.5	208.8	141.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	21.8	[illegible]	7.58	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.83	1.15	0.66
1523A	148	127.85	2262	[illegible]	2154	15.6	175.8	107.3	127.2	241.9	114.9	72.462	41.4	[illegible]	15.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	13.52	1.16	[illegible]
B	148	[illegible]	[illegible]	67.3	2120	18.6	158.9	102.7	132.7	[illegible]	[illegible]	[illegible]	[illegible]	27.7	[illegible]	[illegible]	48.27	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	15.02	1.04	1.00
1524A	149	[illegible]	2272	67.1	2137	15.2	166.5	108.5	142.0	[illegible]	[illegible]	72.710	[illegible]	21.6	17.6	[illegible]	[illegible]	46.20	[illegible]	[illegible]	[illegible]	[illegible]	14.19	1.11	1.04
1525A	151	124.76	2359	68.7	2142	23.4	170.9	108.8	79.8	177.7	[illegible]	[illegible]	[illegible]	26.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.464	[illegible]	[illegible]	14.01	1.12	1.00
1526A	153	[illegible]	2413	73.4	2171	21.8	172.4	107.7	102.7	200.7	[illegible]	72.562	[illegible]	24.2	24.1	[illegible]	6.21	6.21	[illegible]	[illegible]	[illegible]	[illegible]	13.81	1.14	0.97
B	154	126.31	[illegible]	77.4	2137	25.1	170.5	107.7	107.4	[illegible]	[illegible]	[illegible]	[illegible]	31.4	30.7	[illegible]	7.58	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	14.18	1.10	0.97
1527A	155	[illegible]	[illegible]	74.8	2186	24.3	177.3	110.1	75.4	[illegible]	[illegible]	[illegible]	45.1	29.6	26.6	[illegible]	3.45	4.14	[illegible]	.491	[illegible]	[illegible]	13.23	1.14	1.01
B	156	125.97	2606	[illegible]	2160	27.5	182.7	110.1	71.6	[illegible]	77.8	72.567	[illegible]	41.1	27.7	[illegible]	6.21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	13.89	1.13	1.00

GASEOUS FUELS

Test No.	Config. No.	PBO, kN/m²	BPO, kN/m²	TO1, °C	PGF, kN/m²	TGF, °C	DPG, kN/m²	PV1, kN/m²	TV1, °C	TV2, °C	TMF, °C	PM1, kN/m²	TM1, °C	TM, °C	TBI, °C	PA1, kN/m²	DPA1, N/m²	DPA2, N/m²	PAMB, kN/m²	VA, m/s	WA, kg/h	WFG, kg/h	A/FG Ratio	φ ER	HCA ER
1500A	117	129.75	0.2296	65.8	532.9	19.7	222.1	125.5	[illegible]	192.3	109.9	98.79	92.6	16.8	15.6	[illegible]	9.6	9.3	[illegible]	1.432	104.69	8.119	13.29	1.15	0.79
B	117	128.51	0.2394	67.4	518.5	16.9	223.0	123.5	109.7	191.9	85.6	98.79	95.9	37.7	33.7	[illegible]	9.0	9.3	[illegible]	1.457	108.06	7.983	13.91	1.15	0.71
C	117	[illegible]	[illegible]	69.7	526.0	18.7	225.1	[illegible]	132.1	206.9	111.3	74.49	46.4	27.2	25.4	[illegible]	8.3	8.3	[illegible]	1.472	[illegible]	[illegible]	13.69	1.16	0.71
1501A	119	129.38	[illegible]	66.7	510.6	15.7	214.6	123.6	128.6	177.1	[illegible]	74.52	42.5	20.1	17.9	74.330	11.0	12.4	[illegible]	1.420	[illegible]	[illegible]	13.46	1.14	0.69
B	119	[illegible]	[illegible]	68.7	527.4	17.5	225.8	[illegible]	122.1	200.4	99.7	74.41	43.6	25.7	24.1	74.227	11.0	11.0	[illegible]	1.447	[illegible]	[illegible]	13.48	1.14	0.77
C	119	128.74	0.2413	71.7	[illegible]	18.2	222.0	124.6	128.1	177.1	110.6	74.41	49.3	30.2	27.3	74.220	10.3	11.0	[illegible]	[illegible]	[illegible]	[illegible]	13.45	1.14	0.70
D	119	128.21	[illegible]	73.8	531.3	21.0	229.0	[illegible]	127.2	192.7	110.8	74.38	49.6	31.0	25.6	74.177	11.7	11.7	[illegible]	[illegible]	[illegible]	[illegible]	13.60	1.17	0.70
1502A	120	128.47	0.2434	70.4	538.2	18.3	232.2	124.8	131.6	[illegible]	111.8	74.24	49.2	[illegible]	25.3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	13.70	1.16	[illegible]
B	121	[illegible]	0.2448	74.7	523.2	20.1	232.3	123.2	131.7	202.0	112.2	74.05	47.9	33.4	27.7	[illegible]	9.7	10.3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.15	0.68
C	121	127.27	0.2412	70.4	527.9	20.1	228.2	122.0	112.4	180.5	97.8	73.75	46.1	31.4	26.1	[illegible]	10.3	7.7	[illegible]	[illegible]	[illegible]	[illegible]	13.82	1.15	0.69
D	121	127.19	[illegible]	72.7	524.1	[illegible]	224.0	121.5	[illegible]	[illegible]	[illegible]	73.282	45.4	[illegible]	24.9	[illegible]	7.0	7.0	[illegible]	1.467	[illegible]	[illegible]	13.72	1.16	0.68
1503A	122	[illegible]	[illegible]	64.7	[illegible]	[illegible]	207.5	[illegible]	121.1	206.1	107.3	73.575	42.8	17.1	14.7	[illegible]	[illegible]	7.7	73.476	[illegible]	[illegible]	7.666	13.48	1.11	0.67
B	122	127.61	0.2377	67.6	518.8	18.1	[illegible]	[illegible]	131.2	203.4	114.9	73.613	44.3	21.8	20.7	73.407	10.3	11.0	[illegible]	[illegible]	[illegible]	[illegible]	13.72	1.16	0.66
C	122	[illegible]	0.2411	72.7	515.3	17.2	[illegible]	121.1	115.4	191.6	94.8	73.507	45.6	31.6	29.6	[illegible]	10.3	11.7	[illegible]	[illegible]	99.97	[illegible]	13.69	1.17	0.66
1505A	124	130.47	[illegible]	[illegible]	519.9	[illegible]	217.0	124.4	129.7	[illegible]	[illegible]	74.510	43.3	18.7	13.4	[illegible]	35.7	36.5	[illegible]	1.440	[illegible]	[illegible]	13.82	[illegible]	0.73
B	124	[illegible]	0.2241	[illegible]	505.8	14.3	210.4	122.8	130.0	203.6	110.3	74.306	42.7	19.6	18.7	74.317	[illegible]	38.6	[illegible]	[illegible]	[illegible]	[illegible]	13.49	[illegible]	0.71
C	124	129.05	0.2334	67.0	[illegible]	16.5	211.5	122.4	127.2	202.3	107.2	74.234	42.3	[illegible]	21.5	[illegible]	38.6	40.0	[illegible]	1.457	[illegible]	[illegible]	13.97	1.10	0.71
D	124	128.70	0.2331	[illegible]	504.7	15.4	213.2	[illegible]	120.7	203.9	111.7	74.44	46.4	26.9	22.6	[illegible]	[illegible]	40.0	[illegible]	1.454	[illegible]	[illegible]	[illegible]	1.12	0.72
1511A	131	127.76	[illegible]	63.4	507.4	[illegible]	213.2	121.9	126.1	205.1	104.1	73.124	72.8	15.7	13.7	[illegible]	24.8	30.7	[illegible]	[illegible]	[illegible]	7.847	13.11	1.13	0.73
B	131	127.43	[illegible]	66.4	521.8	16.2	224.9	124.8	132.2	201.4	110.8	[illegible]	44.7	21.3	18.7	[illegible]	20.7	20.0	[illegible]	[illegible]	101.79	[illegible]	13.61	1.08	0.74
C	131	126.27	0.2344	67.1	519.8	16.6	223.3	124.1	133.7	[illegible]	112.1	72.995	37.8	26.1	21.8	[illegible]	22.1	22.8	[illegible]	1.451	[illegible]	[illegible]	[illegible]	1.18	0.76
D	131	126.52	[illegible]	70.4	524.9	[illegible]	232.9	121.7	74.8	112.7	65.3	72.772	44.8	28.6	20.9	72.710	[illegible]	[illegible]	[illegible]	1.536	[illegible]	[illegible]	13.09	1.13	0.73
1521B	150	126.85	[illegible]	71.2	507.2	21.4	[illegible]	122.4	[illegible]	202.7	[illegible]	73.572	48.6	31.9	22.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	13.50	[illegible]	0.95
C	150	126.67	0.2412	[illegible]	[illegible]	22.3	[illegible]	119.8	144.2	199.8	[illegible]	73.503	47.8	30.7	25.2	[illegible]	37.92	[illegible]	[illegible]	1.570	[illegible]	7.711	13.45	1.10	0.97
1525B	152	126.54	[illegible]	68.4	527.4	24.0	[illegible]	111.0	129.1	192.6	99.5	73.306	43.7	[illegible]	25.9	[illegible]	[illegible]	24.13	[illegible]	[illegible]	[illegible]	[illegible]	13.32	1.11	0.97
C	152	[illegible]	[illegible]	70.5	510.2	25.5	[illegible]	111.0	136.7	[illegible]	78.8	73.310	44.6	[illegible]	24.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	13.79	1.10	[illegible]

APPENDIX C

TABULAR SUMMARY OF TRANSIENT-STATE MEASURED FLAME SPEED AND PEAK PRESSURE RISE

Test No.	Config. No.	Flame Chamber Test Data: Peak Pressure Rise DP81, N/m^2	DP83, N/m^2	DP85, N/m^2	DP87, N/m^2	Flame Sensor Flame Speeds F81-F82, m/s	F82-F83, m/s	F83-F84, m/s	F84-F85, m/s	F85-F86, m/s	F86-F87, m/s	Photographic Flame Speeds SA-S1, m/s	S1-S2, m/s	S2-S3, m/s	S3-S4, m/s
1495E	112	746	726	741	804	2.04	6.02	2.72	5.89	8.91	N.A.[a]	NA	NA	NA	NA
1496A	113	1053	1048	920	992	4.96	7.01	9.68	18.51	2.09	8.24	NA	NA	NA	NA
B	113	972	718	797	706	5.54	7.62	10.70	15.24	10.89	12.92	2.5	3.39	2.97	3.11
C	113	769	834	838	745	5.5[illegible]	7.53	8.71	7.17	9.23	5.64	2.21	3.11	3.97	4.15
1497A	114	989	1055	955	1031	2.28	2.00	2.05	1.91	1.77	3.60	2.45	1.79	1.56	1.40
B	114	825	888	938	821	3.00	2.90	2.79	2.09	2.38	3.67	2.68	5.08	2.15	1.78
C	114	618	789	978	840	4.32	3.45	3.22	4.72	4.72	3.98	3.84	7.36	2.97	2.49
1498A	115	810	834	883	802	2.82	2.41	2.56	3.11	4.38	4.23	5.11	2.39	1.98	1.66
B	115	729	737	639	725	2.67	2.60	3.09	4.06	4.29	6.59	2.84	2.54	2.79	2.49
C	115	810	718	695	725	2.77	1.81	1.68	2.08	1.40	9.86	3.27	1.91	1.24	1.31
D	115	729	756	752	783	3.06	2.13	2.51	3.91	2.68	3.81	3.41	2.54	1.98	2.08
1499A	116	830	854	846	783	5.08	7.01	8.57	12.19	13.33	11.72	3.95	4.93	9.54	6.22
B	116	891	912	876	783	7.92	6.77	7.26	13.85	15.64	16.47	3.95	4.93	9.54	9.98
C	116	891	892	883	859	5.21	7.26	7.82	18.59	11.02	21.02	4.53	6.10	9.54	6.22
1500A	117	No	IGNITION												
B	117	1060	1099	1028	980	5.25	8.16	7.43	9.38	5.64	12.19	9.78	2.62	5.94	6.22
C	117	1035	1122	960	980	5.28	7.82	8.71	12.62	6.78	15.45	4.28	6.10	5.94	8.30
1501A	118	1013	965	914	763	5.56	7.39	7.97	9.18	6.45	12.77	3.95	4.36	4.95	4.98
B	119	966	987	1005	938	3.54	3.48	2.64	3.56	3.06	6.21	3.78	2.77	2.29	2.26
C	119	898	898	845	785	3.66	3.77	3.28	2.74	2.83	7.32	4.28	3.31	2.70	2.08
D	119	895	920	914	812	2.23	2.89	2.31	2.46	2.69	9.37	4.54	3.39	2.41	1.18
1502A	120	1251	1571	1671	1483	10.84	10.84	9.95	7.78	7.50	11.24	3.13	3.05	7.43	6.22
B	121	769	765	747	698	3.63	3.74	3.11	2.42	1.81	5.87	4.65	3.21	4.25	3.56
C	121	794	790	682	698	2.31	4.04	3.06	2.67	0.97	4.08	3.59	5.08	1.35	1.81
D	121	818	808	858	872	4.67	3.76	2.85	2.23	2.00	5.19	5.19	3.21	3.31	2.08
1503A	122	1342	1472	1234	1158	5.34	7.57	7.20	7.11	20.61	12.20	5.19	5.08	2.93	8.30
B	122	1201	1099	1120	1010	6.79	9.34	8.24	9.49	8.28	15.33	6.79	7.62	7.43	8.30
C	122	1036	1053	1005	1158	4.86	2.66	2.76	2.03	12.87	8.92	4.90	6.00	7.43	8.30
1504A	123	1319	1418	1325	1223	3.39	2.71	6.55	6.77	6.15	7.53	3.40	3.81	4.25	4.98
B	123	1439	1442	1417	1414	4.30	5.29	9.56	10.95	11.37	12.55	3.82	4.73	5.94	8.30
C	123	1413	1396	1393	1265	4.91	6.15	8.32	10.79	16.01	16.90	4.38	5.08	8.68	6.22
1505A	124	1389	1526	1531	1396	8.52	8.89	8.76	13.93	16.58	32.28	3.22	2.57	4.85	4.98

Test No.	Inlet Piping Test Data: Peak Pressure Rise P73, kN/m^2	P72, kN/m^2	P71, kN/m^2	P21, kN/m^2	P12, kN/m^2	Flame Sensor Flame Speeds F81-F73, m/s	F73-F72, m/s	F72-F71, m/s	F71-F21, m/s	F21-F12, m/s
1495E	855.3	265.4	197.0	51.7	217.6	2.32	2.35	2.41	7.23	18.94
1496A										
B										
C										
1497A										
B										
C										
1498A										
B										
C										
D										
1499A										
B										
C										
1500A										
B										
C										
1501A										
B										
C										
D										
1502A	336.5	178.5	304.4	>470	>470	8.70	6.93	8.47	22.53	>1800
B										
C										
D										
1503A	197.6	246.7	285.8	>470	>470	3.69	8.30	7.33	18.68	>1800
B	150.6	252.0	278.2	>470	>470	3.77	2.36	5.92	15.76	>1800
C	196.7	172.3	256.7	>470	>470	4.29	5.37	2.69	15.47	>1800
1504A										
B										
C										
1505A										

[a]N.A. - Not available.

		Flame Chamber Test Data														Inlet Piping Test Data									
		Peak Pressure Rise				Flame Sensor Flame Speeds						Photographic Flame Speeds				Peak Pressure Rise					Flame Sensor Flame Speeds				
Test No.	Config. No.	DP01, kN/m²	DP03, kN/m²	DP05, kN/m²	DP07, kN/m²	F01-F02, m/s	F02-F03, m/s	F03-F04, m/s	F04-F05, m/s	F05-F06, m/s	F06-F07, m/s	S0-S1, m/s	S1-S2, m/s	S2-S3, m/s	S3-S4, m/s	P73, kN/m²	P72, kN/m²	P71, kN/m²	P31, kN/m²	P12, kN/m²	F04-F73, m/s	F73-F72, m/s	F72-F71, m/s	F71-F31, m/s	F31-F12, m/s
1505E	124	1131	1055	1097	1243	7.38	6.95	7.20	7.81	7.75	19.36	3.41	2.39	5.94	8.78										
C	124	1319	1369	1417	1221	6.24	6.88	7.88	11.74	12.74	15.36	7.03	7.39	4.95	7.98										
D	124	1578	1504	1599	1504	6.45	9.01	13.47	15.64	30.30	32.44	6.13	6.10	7.43	12.44										
1506A	125	707	718	731	824	2.67	3.61	1.31	2.36	1.63	2.07	N.A.[a]	N.A.	N.A.	N.A.										
B	125	754	845	845	975	2.83	3.19	1.74	2.30	1.38	3.56														
C	125	942	1032	1097	1113	3.57	4.19	3.97	2.33	1.77	3.32														
D	125	707	809	913	1069	6.38	6.31	2.87	3.92	2.32	2.37														
1507A	126	NO IGNITION																							
B	126	1198	1036	1073	972	6.48	4.46	2.32	N.A.	N.A.	N.A.					153.2	137.6	155.3	109.7	93.8	2.29	4.12	3.48	4.96	[illegible]
C	127	784	907	981	971	7.02	6.82	7.23	5.16	7.97	3.57														
1508A	127	958	994	1005	930	3.79	6.58	2.97	1.60	0.84	0.67														
B	127	1045	1036	1045	1069	3.69	6.70	7.82	5.93	3.11	3.67														
C	128	914	994	965	1148	3.83	2.56	6.13	3.78	1.35	2.04														
	128	1176	1318	1125	1148	4.40	8.67	5.06	4.78	3.04	3.67														
E	128	1350	1274	1429	1237	4.61	8.01	4.64	3.61	3.32	4.35	N.A.	N.A.	N.A.	N.A.										
1509A	129	1595	1569	1647	1527	2.64	3.36	16.34	25.86	42.79	52.01	2.72	N.A.	3.32	3.26	317.9	139.7	300.6	>440	>440	3.63	1.21	6.14	4.80	2.00
B	129	1071	1060	1095	916	2.95	3.31	18.15	30.45	72.11	88.15	2.35	3.05	3.30	4.38	346.6	211.5	297.9	>440	>440	3.43	6.82	1.31	4.02	2.02
C	129	1595	1526	1507	1317	4.57	5.49	25.15	34.14	35.51	60.35	N.A.	N.A.	4.95	4.94	>382.6	152.5	265.3	>440	>440	2.90	1.59	3.12	2.96	3.06
1510A	130	871	858	864	894	2.86	2.41	2.10	2.55	2.60	3.18	1.65	2.03	N.A.	N.A.										
B	130	1089	1101	1305	1382	5.06	4.13	8.35	2.54	2.00	3.65	3.47	3.39	4.35	2.76										
C	130	1132	1034	1226	1363	5.17	6.43	5.49	3.74	2.47	2.69	2.32	4.35	3.30	N.A.										
1511A	131	666	715	733	719	5.24	5.24	6.99	7.83	12.98	17.47	3.98	3.39	5.94	8.76										
B	131	666	787	708	879	7.59	5.91	5.63	8.07	13.89	14.63	4.71	4.36	5.94	7.98										
C	131	745	930	960	777	8.60	8.03	8.88	10.38	11.37	12.39	5.75	6.10	5.94	8.30										
D	131	1243	1168	1234	1166	9.23	8.82	9.84	12.64	12.65	16.29	5.25	6.10	7.43	10.44	355.7	208.5	285.1	318.1	337.7	3.12	6.88	[illegible]	32.03	[illegible]
1512A	132	740	858	868	874	4.35	4.71	2.67	2.86	5.41	N.A.	3.04	3.81	3.32	1.91										
B	132	1307	1454	1380	1127	4.61	5.62	5.57	7.36	8.66	8.51	3.23	4.36	4.95	4.98										
C	132	1067	954	1090	1088	5.35	5.75	5.09	3.22	11.71	9.37	2.04	4.36	5.94	4.15										
1513A	133	980	937	941	933	3.36	6.22	4.68	2.94	N.A.	N.A.	3.49	4.36	4.95	6.32										
B	133	784	721	762	933	3.50	4.55	3.73	2.34	N.A.	N.A.	2.52	3.81	3.32	8.56										
C	133	691	721	784	722	3.16	4.69	2.83	1.34	N.A.	N.A.	2.67	3.81	4.25	4.15										
D	134	784	841	852	1010	4.46	6.63	5.07	4.09	N.A.	N.A.	3.28	4.36	5.94	4.98	186.7	193.5	176.0	338.2	300.1	2.19	2.98	3.90	N.A.	N.A.

[a]N.A. - Not available.

Test No.	Config. No.	Flame Chamber Test Data: Peak Pressure Rise: DPB1, N/m²	DPB3, N/m²	DPB5, N/m²	DPB7, N/m²	Flame Sensor Flame Speeds: FB1-FB2, m/s	FB2-FB3, m/s	FB3-FB4, m/s	FB4-FB5, m/s	FB5-FB6, m/s	FB6-FB7, m/s	Photographic Flame Speeds: SA-S1, m/s	S1-S2, m/s	S2-S3, m/s	S3-S4, m/s	Inlet Piping Test Data: Peak Pressure Rise: PT3, kN/m²	PT2, kN/m²	PT?, kN/m²	PT?, kN/m²	PT2, kN/m²	Flame Sensor Flame Speeds: F01-F73, m/s	F73-F72, m/s	F72-F71, m/s	F71-F2?, m/s	F2?-F1?, m/s
1514A	135	871	828	772	777	3.74	4.95	4.65	4.38	N.A.*	N.A.	2.76	3.81	4.07	4.98										
B	135	871	828	858	855	4.77	5.68	4.90	3.95	N.A.	N.A.	3.53	6.10	4.95	3.56										
C	135	791	828	703	758	5.97	5.89	6.06	4.50	N.A.	N.A.	3.53	6.10	4.95	4.96										
1515A	136	791	731	740	699	4.61	5.08	6.35	2.72	8.66	2.37	2.29	2.77	3.30	3.56										
B	136	805	852	876	952	5.64	6.15	6.63	2.92	2.23	2.71	3.15	4.36	4.95	4.98										
C	136	479	584	583	699	6.55	7.00	7.00	4.94	4.13	4.71	3.68	6.10	4.95	4.98										
D	137	762	706	762	1018	7.29	8.88	9.57	4.03	9.00	3.37	4.90	6.10	4.95	4.70	207	155	131	NA	NA	7.6	[illegible]	5.2	NA	NA
1516A	138	697	654	650	661	3.32	2.10	3.96	1.58	0.61	.29	1.54	1.45	1.98	3.56										
B	138	582	584	493	505	4.87	6.73	5.71	2.82	4.5	2.12	3.02	4.36	3.72	4.15										
C	138	566	561	605	622	4.96	6.33	5.69	2.60	4.10	2.32	3.13	3.39	4.25	[illegible]										
D	138	575	561	583	641	5.49	6.83	5.64	3.10	3.20	2.42	3.99	4.36	3.72	2.76										
1517A	139	791	779	740	633	5.77	5.08	6.38	12.50	4.33	N.A.	2.93	2.54	3.72	4.15										
B	139	1116	1071	896	816	5.12	5.40	9.10	13.04	4.84	N.A.	3.49	3.05	4.35	4.98										
C	139	946	924	941	1069	6.29	6.14	8.89	10.93	4.11	N.A.	4.33	5.08	4.95	6.22										
D	140	610	633	695	632	7.60	8.11	8.57	15.79	10.91	N.A.	5.04	6.10	7.73	8.30	257	166	101	283	497	2.40	3.21	4.01	[illegible]	14.43
1518A	141	1157	1407	1398	1224	3.89	6.01	4.42	7.50	NA	NA	3.68	3.81	5.99	6.22										
B	141	840	811	914	874	4.16	5.94	4.34	NA	NA	NA	2.94	3.05	4.95	4.15										
C	141	840	1169	1211	1166	5.36	6.35	5.08	NA	NA	NA	3.68	5.08	4.95	4.98										
1519A	142	962	935	960	948	2.35	4.96	2.33	2.75	1.63	2.83	1.96	2.03	2.39	N.A.										
B	142	876	901	1028	1028	4.35	5.57	2.22	2.99	1.61	2.31	2.39	2.39	2.98	3.56										
C	142	876	925	914	964	2.40	5.35	4.68	4.61	4.35	3.84	3.15	5.08	3.72	3.56										
D	142	940	1097	820	1024	3.98	5.29	6.22	5.80	4.49	4.60	3.34	4.36	4.25	4.45										
E	143	778	755	845	968	4.17	6.67	4.84	3.63	3.06	4.58	4.41	5.08	4.95	6.22	209	158	113	390	NA	2.26	3.75	5.37	2.55	13.57
1520A	144	945	901	937	877	2.92	3.15	2.08	2.04	0.94	1.28	2.39	2.03	3.32	2.76										
B	144	870	877	868	907	3.12	4.67	2.91	0.34	1.70	1.87	2.39	4.36	2.97	2.76										
C	144	965	934	935	1028	3.90	5.10	2.29	2.64	0.59	0.49	2.67	3.39	3.30	3.56										
1521A	145	1067	1025	1074	968	4.47	5.32	7.59	4.64	6.75	13.20	3.95	3.81	2.95	6.22										
B	145	537	572	578	565	4.38	5.36	5.88	7.29	5.77	4.71	3.78	4.36	4.95	4.98										
C	145	1133	1359	1380	1452	5.34	7.36	22.8	11.61	8.87	24.62	5.67	6.10	7.73	8.30										
D	146	1005	1097	1280	1371	4.93	7.33	6.37	8.35	10.71	15.41	4.33	6.10	5.97	6.22	319	183	237	[illegible]	N.A.	3.22	4.0	2.9	[illegible]	[illegible]
1522A	147	1176	1267	1051	1049	5.43	6.21	6.98	8.57	5.68	7.35	4.01	5.08	4.95	6.22										
B	147	1176	1389	1302	1462	6.61	9.81	8.35	10.55	13.85	16.70	5.32	6.10	5.97	8.30										
C	147	1359	1292	1198	1029	5.92	7.45	7.24	10.33	8.05	6.16	5.19	6.10	7.43	8.30										

*N.A. - Not available.

APPENDIX D

TABULAR SUMMARY OF AVERAGED MEASURED FLAME SPEED AND PEAK PRESSURE RISE FOR FUELS

Fuel Type	Flame Chamber Test Data: Peak Pressure Rise				Flame Chamber Test Data: Flame Sensor Flame Speed						Flame Chamber Test Data: Photographic Flame Speed				Inlet Piping Test Data: Peak Pressure Rise					Inlet Piping Test Data: Flame Sensor Flame Speed				
	DP81, N/m²	DP83, N/m²	DP85, N/m²	DP87, N/m²	F81-F82, m/s	F82-F83, m/s	F83-F84, m/s	F84-F85, m/s	F85-F86, m/s	F86-F87, m/s	SA-S1, m/s	S1-S2, m/s	S2-S3, m/s	S3-S4, m/s	P73, kN/m²	P72, kN/m²	P71, kN/m²	P21, kN/m²	P12, kN/m²	F81-F73, m/s	F73-F72, m/s	F72-F71, m/s	F71-F21, m/s	F21-F12, m/s
PROPANE[a]	1134	1039	1019	774	4.35	[illegible]	7.21	9.74	10.65	12.63	3.43	[illegible]	6.19	5.02	855	365	181	378	318	2.32	2.35	[illegible]	7.63	8.94
PROPANE[b]	787	530	802	818	2.99	2.66	2.54	3.13	7.12	4.16	[illegible]	[illegible]	2.03	1.57	—									
ETHYLENE[a]	1101	931	1110	1067	6.60	7.63	8.64	10.41	13.23	16.23	4.75	4.76	5.87	5.85	[illegible]	315	374	>440	>440	3.9	2.60	[illegible]	16.22	>[illegible]
ETHYLENE[b]	906	955	760	904	4.35	4.98	4.10	4.12	3.33	7.93	4.02	3.61	[illegible]	[illegible]	337	479	304	>440	>440	4.93	6.43	[illegible]	22.53	>100
GASOLINE	973	997	1033	1064	4.32	6.01	5.04	3.34	2.38	2.92	2.42	3.31	3.98	3.92	183	190	155	110	47	3.00	4.12	4.16	4.69	5.47
METHANOL	818	829	813	803	4.35	5.52	4.66	3.38	NA.	NA.	3.19	4.62	4.69	4.63	186	135	176	322	300	2.97	2.98	2.80	[illegible]	NA
TOLUENE	640	645	661	724	5.42	6.27	6.14	3.04	4.24	3.65	3.21	4.11	3.96	4.83	307	155	121	NA.	NA.	[illegible]	[illegible]	2.72	NA	NA.
DIETHYL ETHER	892	928	964	913	5.61	6.06	6.67	11.95	9.77	NA.	3.73	4.18	5.17	3.57	247	166	101	483	447	3.98	7.61	[illegible]	[illegible]	[illegible]
BUTANE	894	913	930	965	3.62	5.07	2.72	2.10	2.29	2.71	3.90	3.58	[illegible]	[illegible]	209	158	113	390	NA.	3.86	3.35	5.32	[illegible]	12.54
ACETALDEHYDE	1050	1135	1096	1129	5.30	6.98	7.23	9.50	9.81	12.11	4.64	5.38	5.94	5.93	314	187	337	460	NA.	3.32	4.01	6.07	[illegible]	44.5

[a] Igniter position upstream.

[b] Igniter position downstream.

APPENDIX E

TABULAR SUMMARY OF TEMPERATURE MEASUREMENTS FOR SUSTAINED BURNING TESTS

Test No.	Config. No.	Time, s	TBA, °C	TBB, °C	TBC, °C	TBD, °C	TBE, °C	TBF, °C
1529A	149	0	21.4	19.2	19.9	18.8	18.1	22.2
		120	27.2	19.7	20.2	48.5	18.9	21.1
		240	47.7	20.4	20.5	72.2	19.4	22.4
		360	55.6	21.1	20.7	144.4	20.2	24.0
		480	58.1	20.4	20.6	232.1	19.3	22.4
		600	60.1	21.0	21.0	474.5	20.1	22.7
		720	61.1	21.7	21.4	755.9	20.7	24.7
		840	62.0	22.5	22.0	767.8	21.2	25.2
		960	63.0	24.2	22.8	772.8	21.6	26.3
		1080	61.8	27.0	22.6	775.7	20.5	25.2
		1200	60.7	37.5	24.9	772.9	22.0	25.4
		1320	60.3	64.0	27.0	772.2	25.0	26.6
		1440	57.5	102.7	35.6	754.2	30.7	27.4
		1560	60.4	172.3	45.5	747.2	42.9	27.7
		1680	106.3	300.7	57.2	738.5	67.2	27.0
		1800	290.5	527.6	83.6	734.4	137.7	26.6
		1860	270.6	577.2	106.5	735.4	175.3	26.7
		1920	152.1	580.6	136.5	915.7	210.1	27.3
1524B	150	0	28.3	26.9	22.1	22.1	26.1	30.0
		60	106.0	27.3	27.3	70.3	26.3	30.1
		90	517.0	27.4	27.4	513.5	26.4	30.1
		120	847.3	27.4	27.2	840.5	26.5	30.2
		150	955.4	27.7	27.4	880.3	26.9	30.3
		180	921.2	27.7	27.6	870.4	27.9	30.4
		210	923.7	55.7	27.0	912.7	37.4	27.7
		240	934.6	225.6	26.8	915.1	78.0	27.7
		270	757.0	812.2	26.7	917.0	714.3	29.7
		300	910.6	743.0	26.9	919.7	870.7	27.8
		330	1006.8	865.0	28.1	897.2	867.0	30.3
		360	1016.0	876.3	31.4	878.6	874.7	31.7
		390	1022.0	865.0	55.9	915.9	877.3	47.4

Test No.	Config. No.	Time, s	TBA, °C	TBB, °C	TBC, °C	TBD, °C	TBE, °C	TBF, °C	TBG, °C
1529B	150	420	1044.6	894.7	203.7	921.1	902.8	190.0	
		450	810.2	896.9	462.7	865.4	912.6	366.7	
1524C	150	0	36.8	28.0	27.1	33.8	27.9	32.7	
		60	84.2	28.1	27.2	77.2	27.9	32.6	
		90	580.9	28.2	27.2	525.2	27.7	32.6	
		120	912.0	28.2	27.2	856.2	27.4	32.5	
		150	896.8	28.4	27.2	881.1	28.0	32.4	
		180	888.7	31.9	27.2	889.4	29.1	32.3	
		210	902.4	52.2	27.3	892.7	36.7	32.2	
		240	952.0	871.8	27.2	897.4	507.7	32.2	
		270	821.7	879.2	27.2	862.6	922.7	32.2	
		300	776.4	876.5	27.5	842.3	920.0	32.8	
		330	781.3	878.2	30.3	855.7	920.7	38.9	
		360	763.6	900.0	540.8	826.8	918.3	281.1	
		390	776.0	912.0	785.1	828.0	925.5	520.3	
		420	771.3	742.7	575.2	824.8	950.9	575.7	
		450	763.9	982.9	496.2	812.9	912.6	305.6	
1525A	151	0	22.5	26.0	25.8	25.5	24.2	22.9	26.7
		120	36.4	26.6	26.2	28.4	24.9	28.5	285.8
		240	43.0	27.1	26.6	77.4	25.2	28.8	322.2
		360	48.6	26.4	26.8	80.5	24.8	27.0	322.8
		480	54.4	26.3	26.1	78.6	24.4	28.1	324.4
		600	61.8	26.8	26.5	78.1	24.8	28.5	347.1
		720	69.4	27.3	26.9	77.1	25.4	29.4	352.7
		840	77.4	27.7	27.4	77.4	25.8	29.3	356.6
		960	85.0	27.7	27.6	77.0	25.8	29.7	353.4
		1080	91.7	27.4	27.1	75.8	25.6	29.1	351.1
		1200	78.6	27.4	27.6	76.2	26.2	29.6	356.8
		1320	105.1	28.4	28.0	76.7	26.7	30.1	346.7
		1440	110.3	27.5	27.2	76.0	25.4	29.6	330.3

Test No.	Config. No.	Time, s	TBA, °C	TBB, °C	TBC, °C	TBD, °C	TBE, °C	TBF, °C	TBG, °C
1525A	151	1560	116.6	27.5	27.1	75.6	25.9	29.2	333.3
		1670	122.1	28.0	27.5	75.8	26.3	29.7	333.4
		1800	127.6	28.1	27.7	75.6	26.8	30.1	333.7
		1860	137.5	28.9	29.2	35.6	27.2	30.4	75.1
1525B	152	0	32.9	28.3	28.6	28.9	32.4	31.3	30.3
		5	28.7	28.3	28.6	32.1	27.5	31.3	71.8
		10	31.1	28.2	28.5	41.7	27.6	31.3	181.8
		15	33.4	28.2	28.4	52.0	27.6	31.3	278.6
		20	35.2	28.3	28.4	60.8	27.6	31.3	347.2
		25	36.6	28.3	28.5	68.6	27.5	31.3	405.5
		30	38.0	28.3	28.4	75.5	27.6	31.2	461.8
		35	37.1	28.3	28.5	81.5	27.6	31.1	497.3
		40	40.1	28.4	28.6	87.7	27.6	31.3	528.1
		41	40.5	28.3	28.4	88.8	27.6	31.3	546.1
		42	40.8	28.2	28.3	90.3	27.5	31.2	554.7
		43	41.1	28.2	28.3	71.8	27.5	31.2	561.8
		44	65.3	65.4	87.8	109.6	68.2	117.3	529.2
		45	66.7	67.6	74.7	107.6	67.3	115.4	514.7
		50	58.6	69.9	111.3	109.8	67.3	108.7	482.2
1525C	152	0	FLAME THROUGH AT 1 MIN 7.0N						
1526A	153	0	89.3	—	—	—	—	—	—
		120	80.8	—	—	—	—	—	—
		240	85.0	—	—	—	—	—	—
		360	84.7	—	—	—	—	—	—
		480	86.0	—	—	—	—	—	—
		600	88.1	—	—	—	—	—	—
		720	87.0	—	—	—	—	—	—
		840	92.4	—	—	—	—	—	—
		960	92.5	—	—	—	—	—	—

Test No.	Config. No.	Time, s	TBA, °C	TBB, °C
1526A	153	1080	94.0	—
		1200	95.5	—
		1320	97.3	—
		1440	97.8	—
		1560	98.4	—
		1680	100.0	—
		1800	102.2	
		1860	65.6	—
1526B	154	0	32.7	30.9
		120	45.9	71.8
		240	47.6	92.2
		360	48.8	94.2
		480	47.8	95.4
		600	48.3	95.9
		720	47.8	97.0
		840	50.3	99.2
		960	51.1	100.5
		1080	51.6	101.4
		1200	51.3	101.0
		1320	52.4	102.0
		1440	53.7	108.8
		1560	54.4	107.8
		1680	54.4	107.3
		1800	54.8	110.5
		1860	32.5	65.6
1527A	155	0	36.5	
		120	97.2	
		240	350	
		360	294.8	
		480	298.5	—

Test No.	Config. No.	Time, s	TBA, °C	TBB, °C
1527A	155	600	390.8	—
		720	[illegible]	—
		840	341.2	—
		960	[illegible]	—
		1080	[illegible]	
		1200	301.3	—
		1320	325.4	—
		1440	337.0	
		1560	377.8	
		1680	367.6	—
		1800	206.3	
		1860	110.3	—
1527B	155	0	26.6	38.4
		120	59.2	158.0
		240	61.0	[illegible]
		360	[illegible]	187.3
		480	62.0	195.6
		600	63.1	191.6
		720	63.4	197.2
		840	64.2	202.8
		960	65.8	194.7
		1080	65.7	196.9
		1200	65.5	188.7
		1320	64.0	179.0
		1440	65.6	189.1
		1560	65.3	187.7
		1680	66.0	194.2
		1800	67.1	204.3
		1880	67.7	207.8
		1980	97.7	188.5